TAMPERE UNIVERSITY OF TECHNOLOGY

VILLE LYYTIKÄINEN

DEVELOPMENT OF DIVERTOR CASSETTE LOCKING TOOL PROTOTYPES ACCORDING TO REMOTE HANDLING REQUIREMENTS

Master of Science Thesis

Examiner: Prof. Jouni Mattila
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ABSTRACT

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Engineering Development is one stage from the huge development method called Systems Engineering. In this Thesis, Engineering Development is studied and applied for two Case studies. The main emphasis is on the Requirements Management, Design and Testing.

Two Remote Handling (RH) capable tools are developed in the case studies: Water Hydraulic Jack (WHJ) and Wrench-Pin Tool (WPT). WHJ is developed from the first prototype and WPT is developed from a concept level. The tools are used remotely for Gradel Cassette locking and unlocking processes by a robot called Water Hydraulic MANipulator (WHMAN) at Divertor Test Platform 2 (DTP2). The Gradel Cassette is a full scale Mock-Up from a Divertor Cassette that will be used in the International Thermonuclear Experimental Reactor (ITER).

The RH specific Requirements are developed by gathering Operator Feedback (OF), performing Potential Problem Analysis (PPA) and Task Description (TD) for the locking process. The Divertor Cassette Locking Tools are designed according to these RH specific requirements. After the design process, the tools are tested in a full scale test environment and the RH requirements are verified.

The development and testing procedure that is performed for the RH tools may be used as a guideline for forthcoming new generation Divertor Cassette Locking Tools.

TIIVISTELMÄ

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Tämä diplomityö on tehty Tampereen Teknillisen Yliopiston (TTY) Hydrauliikan ja Automatiikan laitoksella (IHA). International Thermonuclear Experimental Reactor (ITER) on monikansallinen projekti, jossa IHA on ollut mukana jo vuodesta 1994 lähtien. Tämä tutkielma on osana ITER-projektia.

ITER on projekti, jonka tavoitteena on osoittaa fuusioenergian käyttökelpoisuus tulevaisuuden energiamuotona. Tämä tavoite jakaantuu moniin tieteellisiin ja teknisiin haasteisiin ja tavoitteisiin. Tärkeimpänä tieteellisenä tavoitteena on tuottaa 10 kertaa enemmän energiaa (>500 MW) kuin reaktori kuluttaa (50 MW). Teknisiä tavoitteita on kehittää suuria lämpötiloja kestäviä materiaaleja, superjohtavia magneetteja, ohjausjärjestelmiä ja etäoperoituja huoltolaitteistoja, jossa IHA on ollut mukana.

ITER-reaktori koostuu donitsin muotoisesta tyhjiöastiasta (Vavcuum Vessel (VV)), jonka pohjalla on niin kutsuttu Diverttori-alue. Tämä alue koostuu 54 Diverttori-kasetista, joita pitää huoltaa säännöllisesti muutaman vuoden välein. Diverttori-kasetit täytyy hakea tyhjiöastiasta huollettavaksi ja palauttaa takaisin huoltotoimenpiteiden jälkeen. Kasetit haetaan ja palautetaan etäoperoidusti (Remote Handling (RH)) päärobotilla (Cassette Multifunctional Mover (CMM)). Tämän päärobotin päälle on integroitu vesihydraulinen manipulaattori (Water Hydraulic MANipulator (WHMAN)), joka avustaa päärobottia vaikeimmissa ja monimutkaisimmissa tehtävissä. Tässä diplomityössä tullaan kehittämään kaksi työkalua, joita käytetään manipulaattorilla Diverttori-kasetin lukitsemiseen ja avaamiseen etäoperoidusti.

Ensimmäinen kehitettävä työkalu on Diverttori-kasetin esijännittävä, vesihydraulinen tunkki (Water Hydraulic Jack (WHJ)). Tunkin tehtävä on puristaa Diverttori-kasettia niin, että se saavuttaa sille tarkoitetun aseman ja muodon. Tästä työkalusta on olemassa ensimmäinen prototyyppi, mutta se ei ole etäoperoitava joten se tarvitsee lisäkehitystä.

Toinen kehitettävistä työkaluista koostuu Pinni- ja Wrench työkaluista (Pin Tool (PT), Wrench Tool (WT)). Näiden kahden työkalun lähtötasot ovat konseptitasolla, joten niitä voidaan kehittää täysin vaatimuksien mukaan. Nämä työkalut tullaan integroimaan yhteen runkoon (Wrench-Pin Tool (WPT)), jonka ansiosta säästetään yksi työkaluteline varalle.

Kehitysprosessin aluksi määritetään erityiset etäoperointi-vaatimukset, joiden mukaan työkalut tullaan suunnittelemaan. Vaatimuksien kehittämisen jälkeen alkaa varsinainen työkalujen suunnitteluosuus. Suunnitteluosuudessa tarkastetaan yksittäisten suunnitelmien, komponenttien ja rajapintojen toiminnallisuus. Tämän jälkeen työkalut integroidaan ja valmistettujen työkalujen toiminnallisuus testataan etäoperoidusti.

Tässä diplomityössä noudatetaan järjestelmäsuunnittelun (Systems Engineering (SE)) toimintaperiaatetta. Järjestelmäsuunnittelu on monitieteellinen kehitysmetodi, jota käytetään kompleksisten systeemien kehittämiseen, joista esimerkkeinä ovat ITER, National Aeronautics and Space Administration (NASA) ja auto- ja lentokoneteollisuus.

PREFACE

This Master of Science Thesis has been undertaken at Tampere University of Technology at the Department of Intelligent Hydraulics and Automation. This study is part of multinational ITER project which IHA has participated since 1994 under association EURATOM-TEKES-contract.

I would like to express my gratitude to the supervisors of the work Professor Jouni Mattila and M.Sc. Pasi Kinnunen for guidance.

Special thanks for the support and encouragement I would to address to my family and especially to Salla and our unborn child.

Tampere 23.5.2012

Ville Lyytikäinen

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ABREVIATIONS AND NOTATION

CC	Central Cassette
CCEE	Central Cassette End-Effector
CLS	Cassette Locking System
CMM	Cassette Multifunctional Mover
CTM	Cassette Toroidal Mover
DEMO	Demonstration Power Plant
DoF	Degree of Freedom
DRM	Divertor Region Mock-Up
DTP2	Divertor Test Platform 2
EE	End-Effector
FEA	Finite Element Analysis
I&E	Integration and Evaluation
IHA	Department of Intelligent Hydraulics and Automation
IR	Inboard Rail
ITER	International Thermonuclear Experimental Reactor
NASA	National Aeronautics and Space Administration
OF	Operator Feedback
OR	Outboard Rail
PT	Pin Tool
PPA	Potential Problem Analysis
RH	Remote Handling
SC	Second Cassette
SCEE	Second Cassette End-Effector
StC	Standard Cassette
StCEE	Standard Cassette End-Effector
TD	Task Description
TEKES	Finnish Funding Agency for Technology and Innovation
TOKAMAK	Toroidal Chamber in Magnetic Coils
TS	Test Stand
TUT	Tampere University of Technology
VTT	Technical Research Centre of Finland
V&V	Verification and Validation
VV	Vacuum Vessel
WHJ	Water Hydraulic Jack
WHMAN	Water Hydraulic Manipulator
WPT	Wrench-Pin Tool
WT	Wrench Tool

1 Introduction

1.1 Background of the ITER Project

International Thermonuclear Experimental Reactor (ITER) is a large-scale scientific and technical project intended to prove the viability of fusion as an energy source. The scientific goal of the ITER is to produce 500 MW of fusion power which is ten times more than it consumes. Technical goals of the ITER Project are to test and to implement key technologies for future fusion power plants including heating, control, diagnostics, and remote maintenance. The ITER is cooperation project between China, European Union, India, Japan, Korea, Russia and USA. The ITER Construction lies at Cadarache in South France and it will be ready for operation in 2019. Planned lifetime of the reactor is 20 years. The ITER Project is a bridge towards a first fusion power plant that will demonstrate the large-scale production of electrical power; the Demonstration Power Plant (DEMO). [1]

Fusion is the process which powers the sun and the stars. In the fusion reaction two light atoms fuse together forming a new atom and tremendous amounts of energy. In the ITER two Hydrogen isotopes (Deuterium and Tritium) fuse together forming a Helium nucleus, a Neutron and lots of energy. Deuterium is extracted from water and Tritium is produced during the fusion reaction through contact with Lithium. In order to realize the fusion reaction, gases need to be heated to extremely high temperatures. Required temperature is about 150 million Celsius which over ten times higher than in the sun. At that temperature gases become plasma which can be described as an electrically-charged gas. Extremely hot plasma is contained in a doughnut shaped vessel using superconductive magnets. This kind of reactor is called Tokamak and it is the most advanced and investigated fusion device design. A cutaway view of the ITER Tokamak reactor is shown at Figure 1. [2; 3]

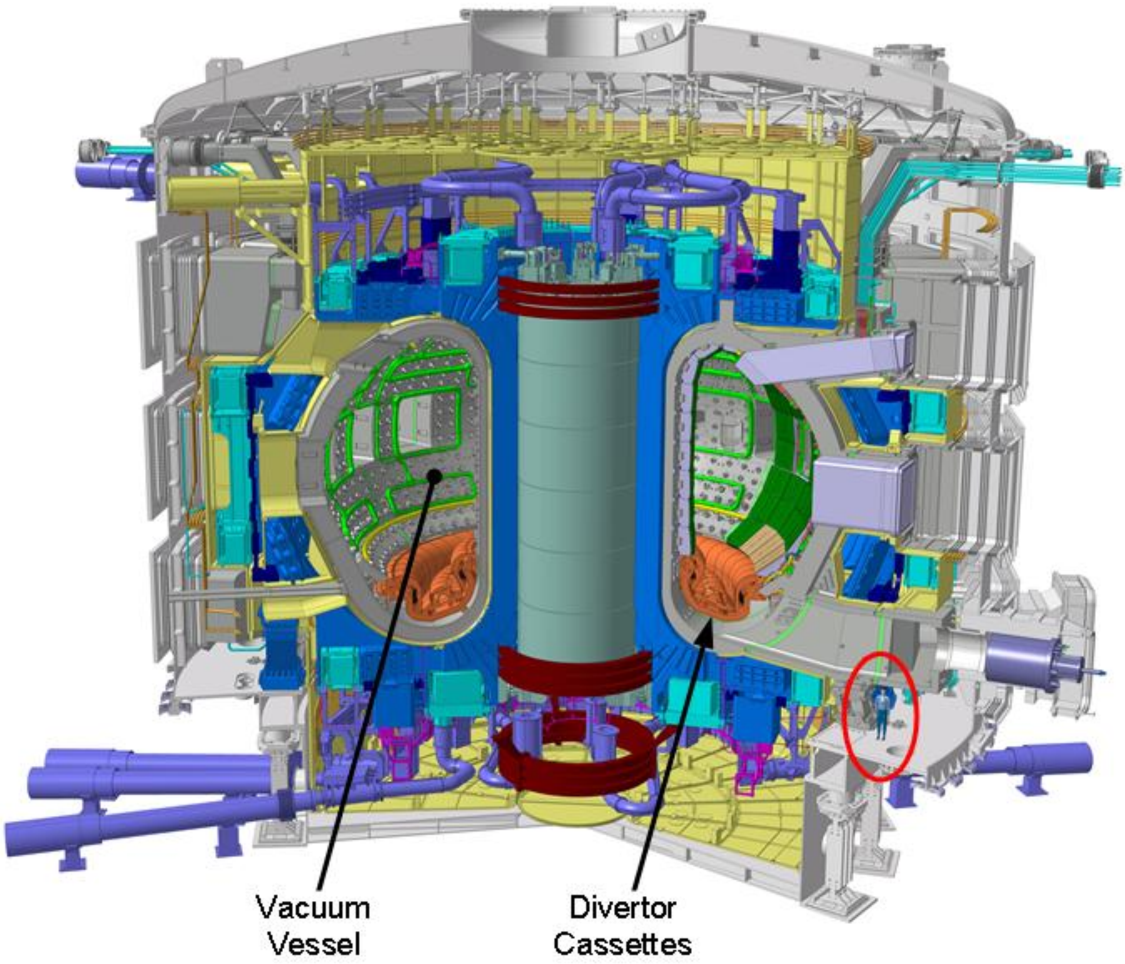

Figure 1: Cutaway of the ITER Tokamak [1]

At the right corner of Figure 1 is highlighted a human dressed in blue which illustrates a scale of the ITER Tokamak reactor; total height of the reactor will be nearly 30 meters. In the middle in Figure 1 is the heart of the ITER, torus-shaped Vacuum Vessel (VV). At the bottom of VV is located the ITER Divertor region (orange part of the reactor). Function of the Divertor is to extract Helium ash, heat, and other plasma impurities from the VV. The Divertor includes 54 remotely-removable cassettes and they needs to be maintained regularly every third year. The maintaining of Divertor cassettes occurs via specially designed Remote Handling (RH) maintenance robots because of Gamma radiation and high loads of the components. [1]

Department of Intelligent Hydraulics and Automation (IHA) from Tampere University of Technology (TUT) and Technical Research Centre of Finland (VTT) are working with RH maintenance robots. Divertor Test Platform (DTP2) is used to demonstrate proof-of-concept level operations with remote handling of the ITER maintenance robotic devices, from a dedicated control room [4]. The DTP2 facility comprises full scale Mock-Ups of the Divertor region systems. The DTP2 is located at VTT Systems Engineering, Tampere and it is being hosted and operated by the Finnish Fusion Association Tekes. IHA has been participating in the ITER project since 1994 [5].

1.2 Scope of the work

Systems Engineering is multidisciplinary development method which is applied for complex development projects e.g. NASA (National Aeronautics and Space Administration), nuclear power industry (like ITER) and aeroplane and car industry. Systems Engineering is separated into three main development stages: Concept Development, Engineering Development and Post Development. All these stages are subdivided into various phases, e.g. Engineering Development includes three individual phases: Advanced Development, Engineering Design and Integration & Evaluation. This thesis studies these three phases and applies them for RH tools.

Few Systems Engineering projects for ITER have been done at the IHA. Concept Development stage for Water Hydraulic MANipulator (WHMAN) tooling concept and Engineering Development stage for Sliding Table are studied by Kinnunen. [6] Engineering Development, focused on the designing process of the WHMAN, is studied by Valkama. [7] Takalo has designed, manufactured and verified the first prototype of Water Hydraulic Jack (WHJ). [8] A gap between design verification (e.g. Finite Element Analysis and simulations) and finished products has been left unaddressed in the earlier studies. [6, 7] This thesis concentrates to the gap by studying different tests for RH tools at various levels on Engineering Development stage.

The first WHJ prototype by Takalo is the initial state for development of the WHJ. Operational requirements of the WHJ prototype are verified [8], but it requires modifications for RH use and therefore it will be developed once more. Other RH tools to be developed are Pin tool (PT) and Wrench Tool (WT). The PT and WT are developed from a concept level.

This thesis constructs as follows: at first overview of ITER Divertor maintenance research facility is introduced in chapter 2. Chapter 3 describes the Systems Engineering theory of Engineer Development; main emphasis is on the requirements and their verifications. In chapters 4, RH specific requirements are developed by Requirement Management methods for Divertor Cassette Locking Tools. After that, in chapter 5, the tools are designed according to these requirements. In this chapter, the functionalities of designs, components and interfaces are verified individually via tests. Next, in chapter 6, the tools are integrated and the RH requirements are verified via system testing. The conclusions of the thesis and recommendations for further studies are finally presented in chapter 7.

2 Overview of the Divertor Test Platform

Development of ITER maintenance devices is a very challenging process. Designed devices must be very reliable, remote handle-able and also compact. Divertor Test Platform (DTP2) is a test facility that is used to mitigate problems and risks via testing and finally proofing the designed concepts.

This chapter introduces all mechanical components at the DTP2. Also a system configuration for one precise remote handling process is introduced. The largest single part at the DTP2 is Divertor Region Mock-Up (DRM) that is shown in Figure 2.

Figure 2: Divertor Cassette Mock-Up installed on the Divertor Region Mock-Up [7]

2.1 Divertor Region Mock-up

The main structure at DTP2, called DRM, is a full scale Mock-Up from ITER Divertor Cassette maintenance area. DRM includes a maintenance tunnel and a 27° section of

ITER reactor vessel (positions for four Divertor Cassettes). At the current DRM it is possible carry out RH operations for Cassette Multifunctional Mover (CMM) equipped with a Second Cassette End-Effector (SCEE) and Second Cassette (SC). In near future the DRM will be expanded to 80° section that allows RH operations with Cassette Toroidal Mover (CTM) and Standard Cassette (StC) [5.]. A section view from the current DRM with CMM, SCEE and Second Cassette (SC) are shown in Figure 3.

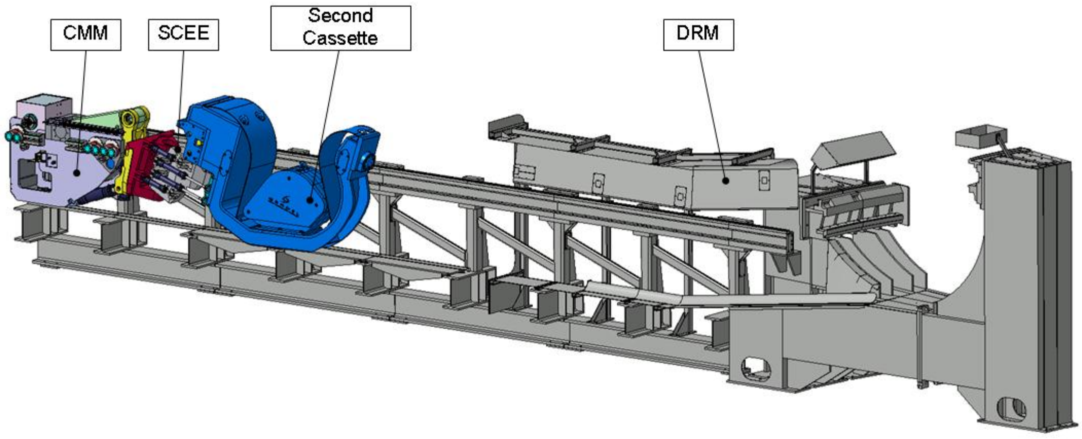

Figure 3: The Divertor Region Mock-Up with Cassette Multifunctional Mover, Second Cassette End-Effector and Second Cassette

Divertor maintenance devices employ mainly hydraulics for motion control excluding few exceptions. Main reasons for choosing hydraulics (instead of electric) are very high payloads and accuracy requirements. High power-to-weight ratio and controllability of hydraulics are also advantages for remote handling devices that are operated in a limited space. All hydraulic systems at DTP2 (and thus at ITER) uses demineralized water as a pressure media instead of traditional oil. The main reason for this is that gamma radiation from the ITER reactor doesn´t affect to water. Other benefit is that demineralized water eliminates the risk of contaminating the reactor elements. Maintenance devices are introduced more specific in following sections.

2.2 Cassette Multifunctional Mover and End-Effectors

CMM is the main robot for the cassette transportation; it is used to move Divertor Cassettes to Vacuum Vessel (VV). CMM has three Degree of Freedoms (DoF) that are realized with hydraulic and electro-mechanic actuators. Two redundant electric servo motors provide reliable linear motion for the CMM. Cassette lifting and tilting movements are accomplished with water hydraulic cylinders because of cassette high payload and positioning accuracy. CMM is equipped with additional tooling (End-Effector, EE) for different maintenance tasks. At the moment CMM is equipped with Second Cassette End Effector (SCEE, shown in Figure 4). SCEE has two additional vertical Dof´s that enables positioning of left hand Second Cassette.

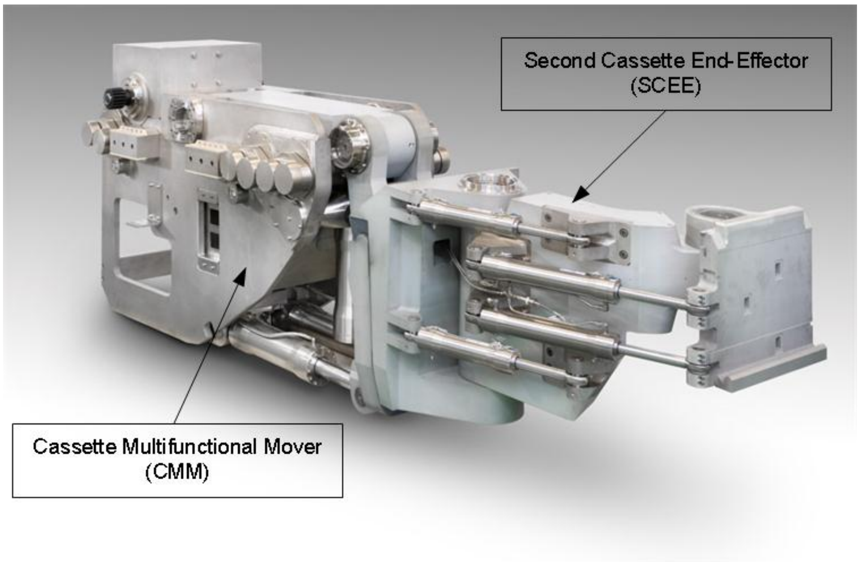

Figure 4: Cassette Multifunctional Mover attached with Second Cassette End-Effector

Divertor Cassettes are named depending on their locations compared to the maintenance tunnel (shown in Figure 5 excluding Standard Cassettes).

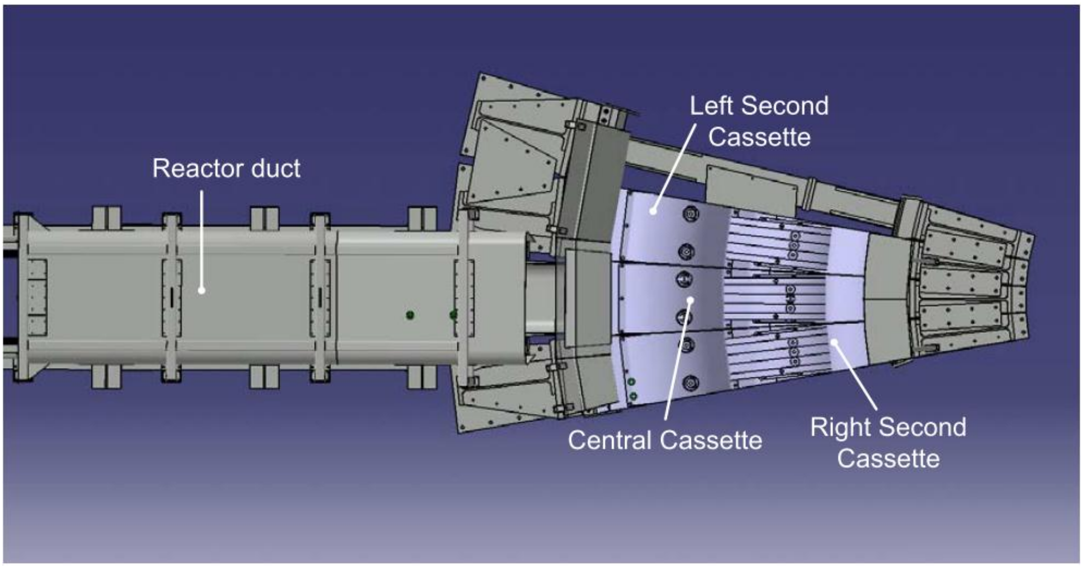

Figure 5: Cassette naming and locations at DRM [6]

2.3 Water Hydraulic Manipulator

Multipurpose robot, called Water Hydraulic Manipulator (WHMAN), is located on the top of main movers CMM/CTM. WHMAN is developed at IHA and more specific details of its design can be found in reference [7]. Main purpose of WHMAN is to assist main movers in more complex maintenance. For example, bolting and gripping, cooling pipe cutting and welding, Divertor cassette locking and unlocking processes are tasks for WHMAN. WHMAN consist six revolute joints and one prismatic joint that are accomplished with water hydraulic vanes and cylinder. WHMAN is installed on linear sliding table that improves flexibility and reachability of WHMAN. In Figure 6 is presenter the WHMAN equipped with the Gripper tool.

Figure 6: Seven-joint Water Hydraulic Manipulator installed on Test Stand Sliding Table [7]

Manipulator tooling

Water Hydraulic Manipulator is equipped with an ability to use different tools in order to accomplish complex processes. The last joint of the WHMAN consist of six axis force sensor (JR3) and the tool exchanger interface. The tool exchanger interface provides following connections for RH tools: high pressure water (10 lpm @ 210 bar, supply and tank lines), pneumatic lines (6 bar) and 17 pins for electrical connections [7]. Various connectors allow usage of following tools [7]:

1) Bolting tool
2) Gripper
3) Pipe cutter tool
4) Pipe welding tool
5) Seal cutting tool
6) Visual inspection tool
7) Vacuum extractor
8) Wrench tool
9) Pin tool
10) Water Hydraulic Jack

2.4 Divertor Cassettes

The ITER Divertor region comprises in total 54 Cassettes that composes the lower part of Vacuum Vessel. Main purpose of Divertor Cassettes is to collect impurities and extract heat from the VV. Divertor Cassettes are designed to be replaced several times during the ITER lifetime. Due to harsh operation conditions (Gamma radiation, vacuum, high temperature and high payload) the realistic way to replace Divertor Cassettes is by means of remote handling maintenance devices. Divertor Cassette weights approximately 9 tonnes (presented in Figure 7).

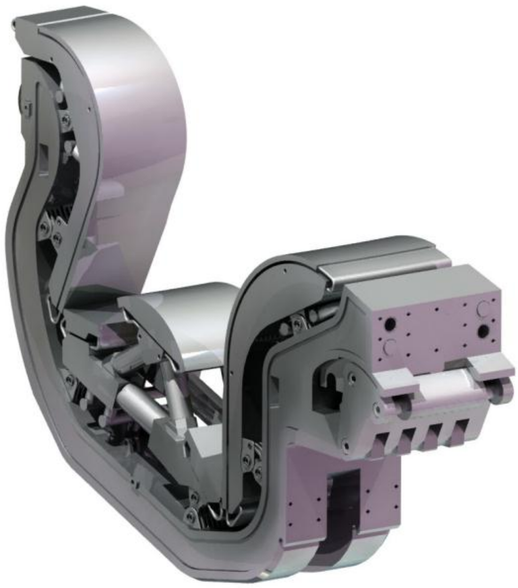

Figure 7: Divertor Cassette [7]

Divertor Cassettes requires appropriate locking between Inboard Rail (IR) and Outboard Rail (OR) in order to remain stationary under plasma operations. Every Divertor Cassettes has a Cassette Locking System (CLS) which is employed via WHMAN to lock Cassettes into their nominal condition for the plasma operations. CLS of Gradel Cassette Mock-Up is presented in Figure 8. This cassette is a little different with the real Divertor Cassette (see Figure 7) that is on the way to DTP2.

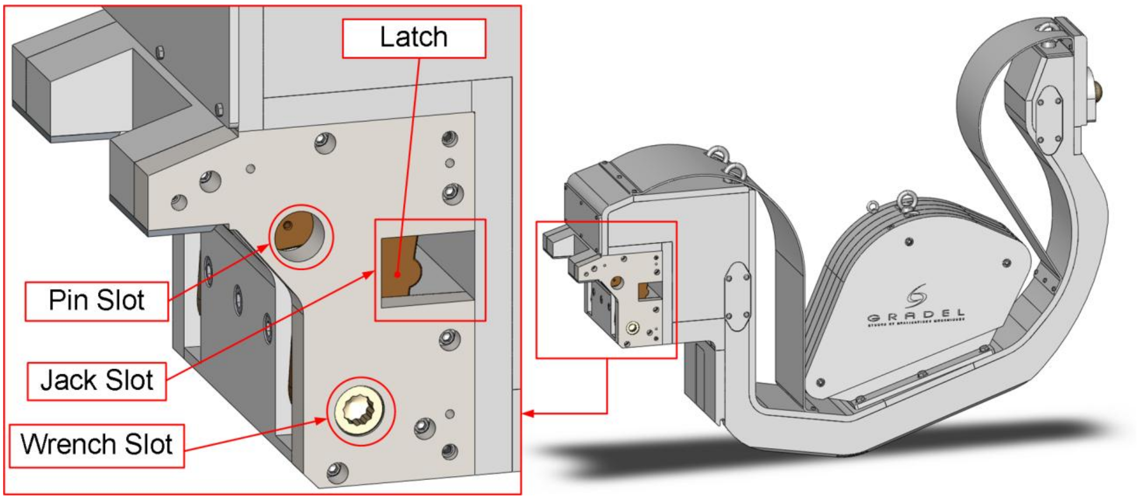

Figure 8: CLS of the Gradel Cassette Mock-Up

The Test Stand (TS) (presented in Figure 9) has been constructed at the DTP2 for independent WHMAN test trials. Test Stand is used for testing of CLS Tools before final tests where WHMAN is installed on CMM.

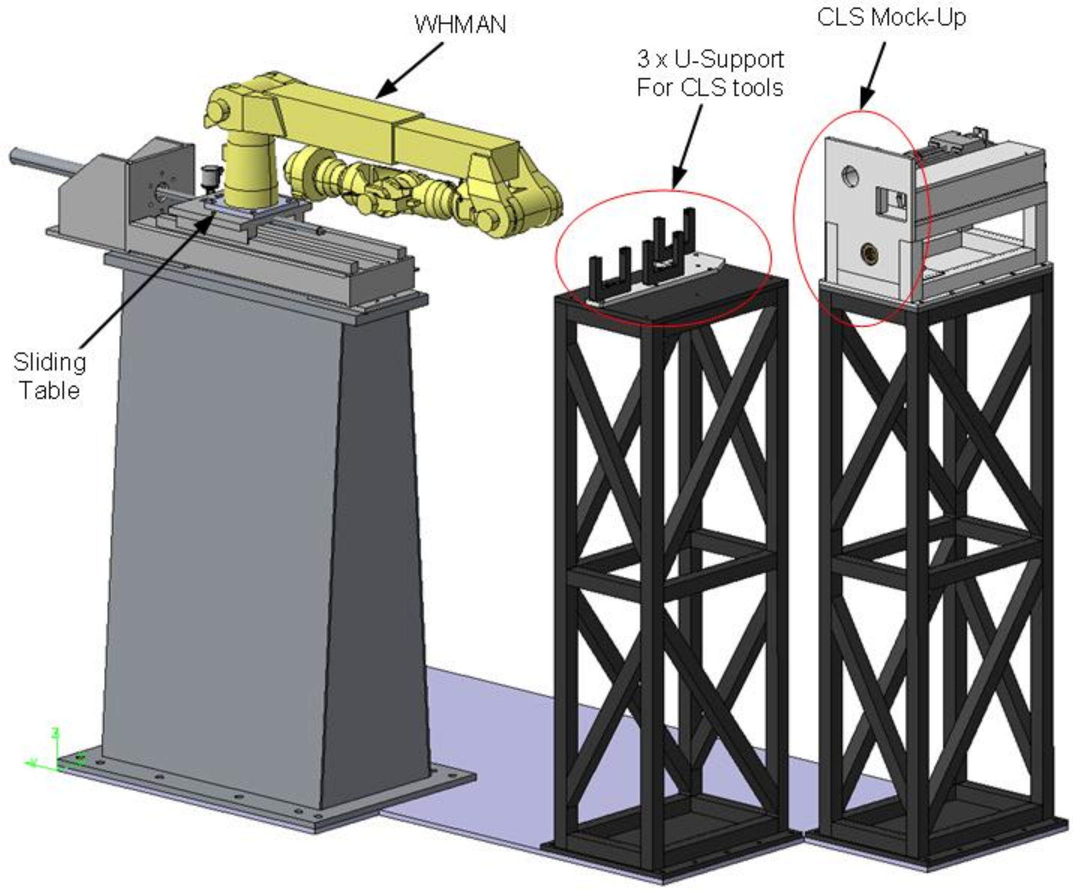

Figure 9: Delmia model of the Test Stand

Test Stand is a testing environment for WHMAN only, as Figure 9 illustrates. It consist WHMAN installed on the Sliding Table, three places for CLS tools and CLS Mock-Up.

2.5 System Configuration for Second Cassette Locking process

Second Cassette Locking process is a part of the bigger process called Second Cassette Installation. The Locking part occurs after the SC has been aligned on the Divertor rails and it is performed via WHMAN. The interface map of the Second Cassette Locking process is illustrated in Figure 10 and the system configuration for the process in Figure 11 respectively. The main operations for the Locking process are presented after the figures in Table 1.

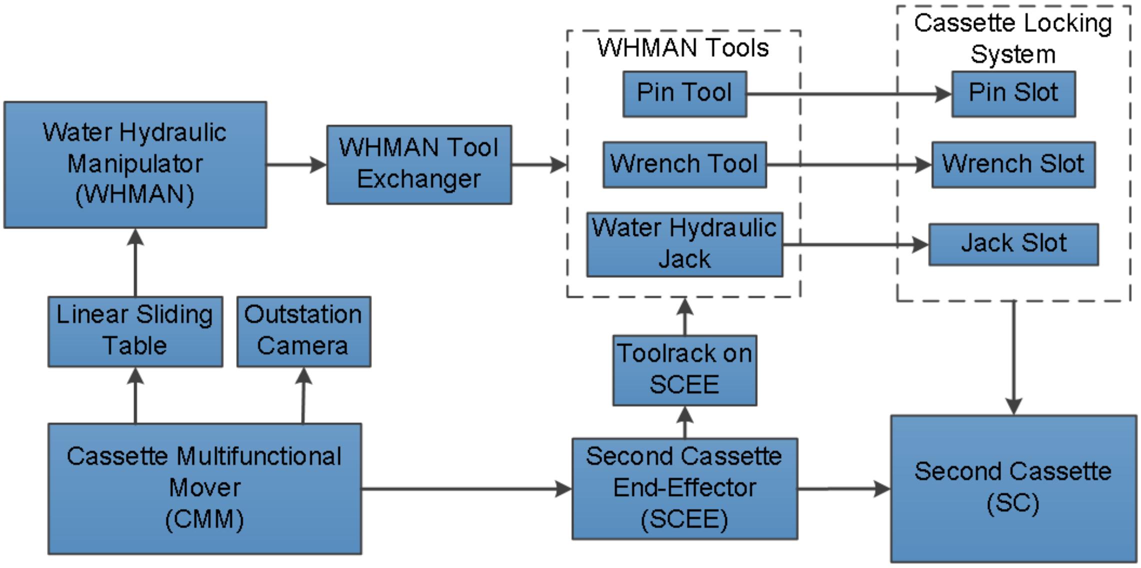

Figure 10: Interface map for Second Cassette installation/ locking process

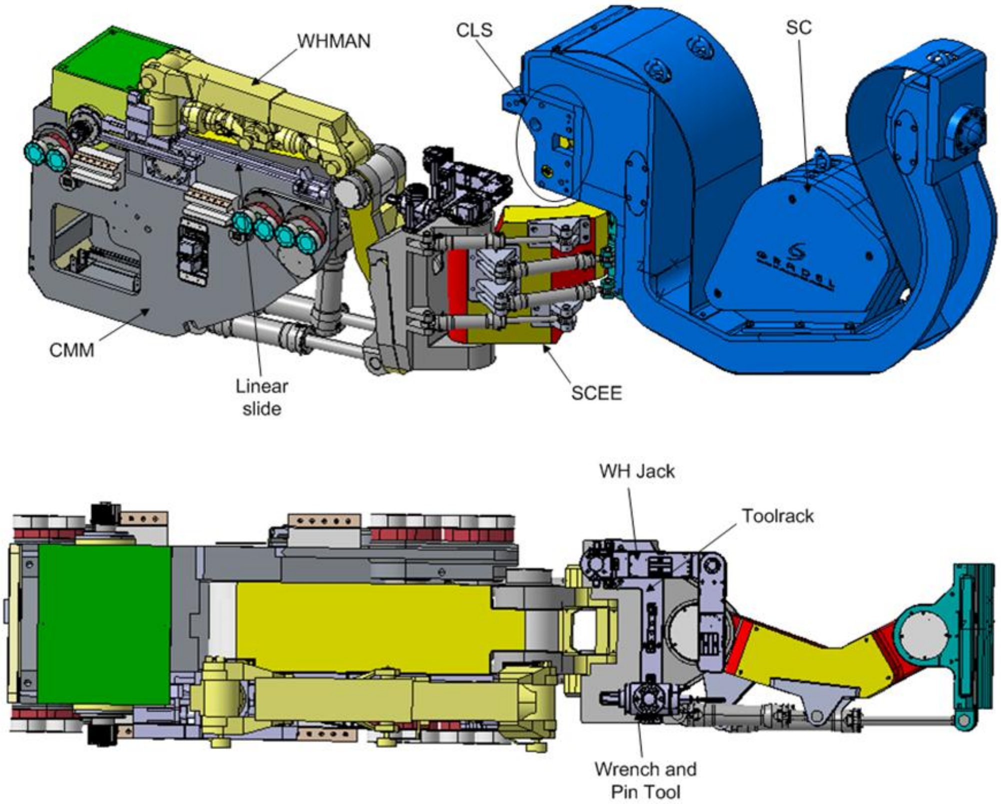

Figure 11: System configuration for Second Cassette Installation/ Locking process

Table 1: Remote Handling Task Description for Second Cassette Locking

Task Description	Locking of the Second Cassette in the DRM
Task Objective	
• To move CMM/SCEE joints to the zero position • To unfold WHMAN at the zero position of the CMM • To connect the Wrench Tool to WHMAN • To rotate the Latches of the Second Cassette • To connect Water Hydraulic Jack to WHMAN • To compress the Second Cassette • To connect the Pin Tool to WHMAN • To lock the Second Cassette Locking mechanism	
Target Plant	
• Second Cassette	
Start Point	
• SCEE is supported by CMM in cantilever manner • SC is disengaged from SCEE and is resting on the DRM • WHMAN is folded	
End Point	
• SC is locked inside the DRM • WHMAN is folded	
Assumptions	
• The elastic deformation of SC and remote handling equipment – induced by gravitational loads - has been neglected during the analysis of the boundary conditions in the assembly process.	
Main Issues	
• The bending of the Second Cassette (together with CMM/SCEE) is not considered during the transportation. Structural flexibility may cause changes to the SC installation sequence.	

Task Description of the Locking process (objectives presented in Table 1) will be studied precisely in Delmia environment later in this thesis. However these studies will ignore the material deformations or structural flexibility because they are impossible to accomplish in the time limits of this thesis.

3 Engineering Development

The System Engineering approach is delineated by Kossiakoff, Sweet, Seymour and Biemer [10] (entire book). Kossiakoff et al. describe that "Systems Engineering viewpoint is focused on producing a successful system that meets requirements and development objectives, is successful in its operation in the field, and achieves its desired operating life." [10, p. 38]

Kossiakoff et al. divide system life cycle into three main development stages and subdivide them into eight individual phases (shown in Figure 12). This thesis concentrates on Engineering Development stage and predominantly on the testing over this stage.

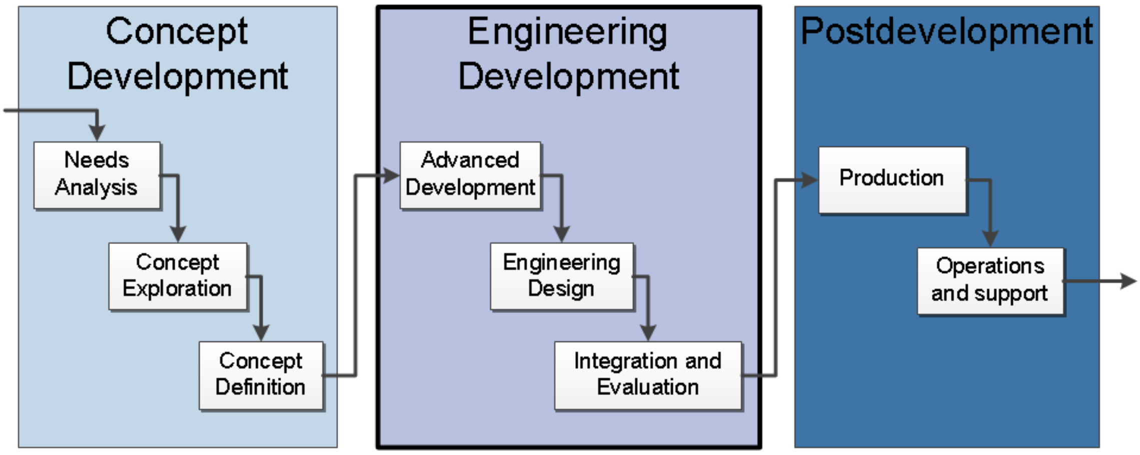

Figure 12: System life cycle model [10, p. 72]

The system development process can be considered as a steps in which the system gradually evolves from abstract requirements to concepts and finally to physical and functional products or systems. Materialization in the Engineering Development phase is compiled Into Table 2. In the Concept Development stage principal status is "define" whereas in Engineering Development stage principal status are "validate", "design" and "test" respectively [10].

Table 2: Status of System materialization at the Engineering Development stage [10]

Level\ Phase	Advanced Devel-opment	Engineering Design	Integration and Evaluation
System	Validate concept		Test and evaluate
Subsystem	Validate subsystem		Integrate and test
Component	Define Specification	Design and test	Integrate and test
Subcomponent	Allocate functions to subcomponents	Design	
Part		Make or buy	

The flowchart of the engineering development process is illustrated in Figure 13. Green lines state proceeding of the process and red lines either verification or update operations. These operations enable the iterative development process.

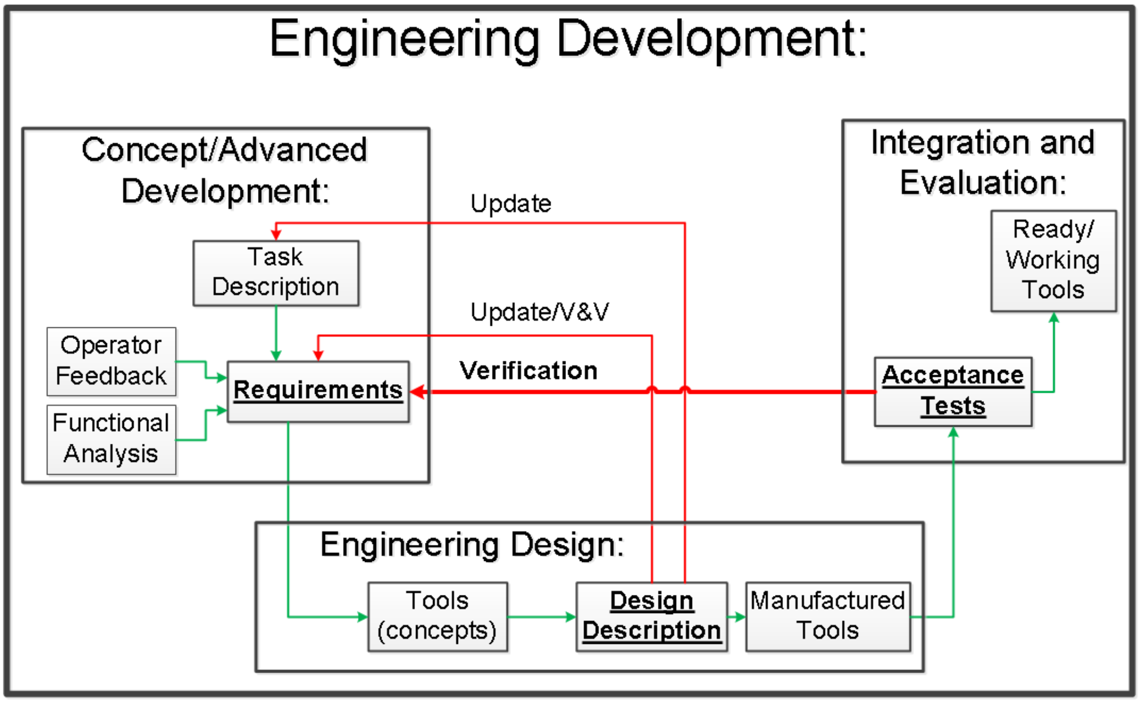

Figure 13: Progress of the development process

3.1 Advanced Development

According to Kossiakoff et.al “the Advanced Development phase is that part of the system development cycle in which the great majority of the uncertainties inherent in the selected system concepts are resolved through analysis, simulation, development, and prototyping.” [10, p. 317.] Figure 14 illustrates Advanced Development phase in system life cycle with inputs and outputs, and main tasks.

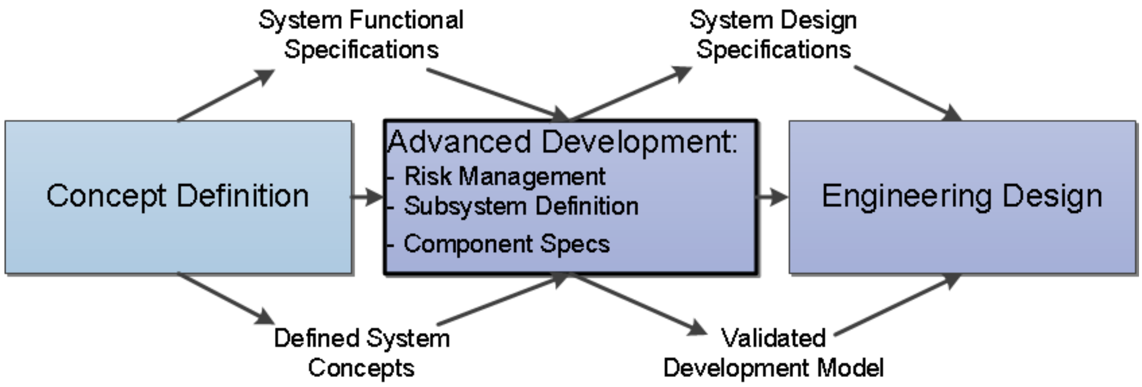

Figure 14: Advanced Development phase in system life cycle [10]

The principal purpose of this phase is to reduce potential risks in the system development to an accepted level. However, a formal advanced development phase does not have to go through “if all major subsystems are directly derivable from proven predecessor or otherwise mature subsystems, and their characteristics can be reliably predicted.” [10 p. 318.] This section concentrates on risks mitigation by requirements analysis instead presentation of formal Advanced Development phase.

3.1.1 Requirements Analysis

Requirements play a vital role in every stage of system development; i.e. requirements create the ground of system development process. In advanced development phase requirements are used to identify components that require more development [10 p. 319]. Requirements Engineering is wide engineering branch and it shall be examined carefully in Concept Development phase. Hull, Jackson, and Dick has presented comprehensive theory of Requirements Engineering in reference [11] (entire book) and that will be applied partly in this development process. Requirements are divided into different levels, depending on their specificity (shown in Figure 15).

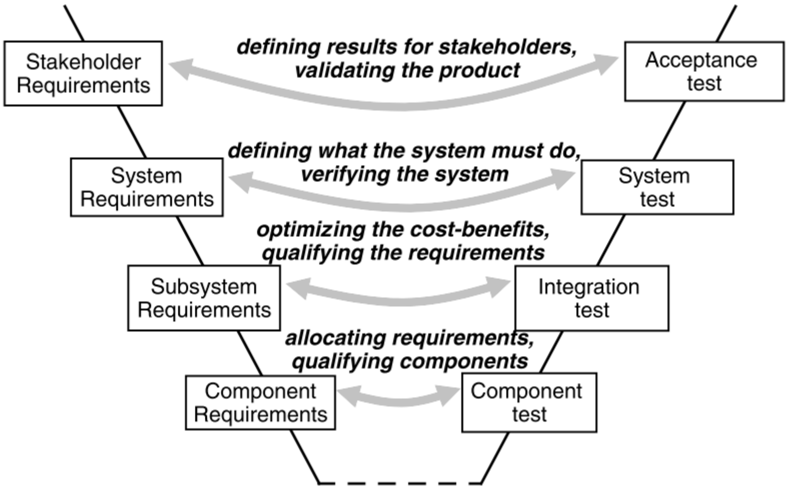

Figure 15: Requirements engineering in layers [11]

In Figure 15 is the classical V-model that presents the various layers in system development process: requirements are at the left side and tests are at the right side. Requirements are derived from high level requirements (stakeholder requirements) to lower level requirements (system, subsystem and component requirements). The links between various requirements in the development process is maintained by tracing requirements between different layers, i.e. traceability. Links between requirements and test are maintained by qualification actions i.e. Verification and Validation.

Traceability

Maintaining of traceability of requirements is mandatory in complex system development process that has many different requirements at various layers. Traceability contributes many benefits in development process and the most beneficial is that it "allows greater confidence in meeting objectives. Establishing and formalizing traceability engenders greater reflection on how objectives are satisfied." [11, p. 10.] The main purpose of traceability is to maintain the links between various requirements. Furthermore, traceability indicates how requirements are satisfied i.e. it keeps also the links between test and requirements (shown in Figure 16).

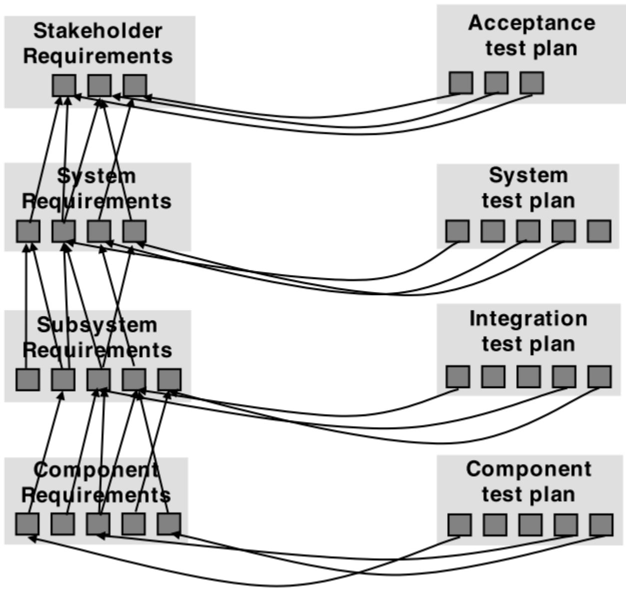

Figure 16: Requirements traceability [11]

As Figure 16 illustrates, requirements and tests are closely related at every layer. According to Hull et al. “testing can be described as any activity that allows defects in the system to be detected or prevented, where a defect is a departure from requirements.” [11, p. 15.] This allows dividing of qualification actions at every level of requirements and test (Table 3).

Table 3: Qualification strategy [11]

Level	**Stakeholder Requirements**	**System Requirements**	**Subsystem Requirements**	**Component Requirements**
Qualification Action	Reviews	Design inspections	Analysis	Prototypes
Level	**Component test**	**Integration test**	**System test**	**Acceptance test**
Qualification Action	Component tests	Rig tests	System tests	Trials

Verification and Validation

Verification and Validation (V&V) process is qualification action that ensures the fulfilment of requirements that are predefined. The main objective of V&V process is to evaluate system which is being developed by identifying potential defects and it spans over system life cycle. [12, p. 76] In systems engineering usual definitions for these terms are:

- ***Verification:*** "The process of determining that a model or simulation implementation and its associated data accurately represent the developer's conceptual description and specifications." [13, p. 10.]
- ***Validation:*** "The process of determining the degree to which a model or simulation and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model." [13, p. 10.]

Informally term *verification* answers to question "Are we building the system right?" and respectively term *validation* to question "Are we building the right system?" [12, p 75] In mechanical engineering usual V&V process includes following techniques: testing, simulation, model checking, and theorem proving. [12. p.76]

3.1.2 Requirements Development Methods

In this subsection, requirements development methods are presented. With assistance of these methods a special requirements for Remote Handling (RH) are investigated. The main objectivity of the developing of RH requirements is to construct solid ground for development of reliable and robust RH tools. This phase can be described as the end of Advanced Development phase i.e. in this phase risks and components that require more development are identified.

Virtual Prototyping

According to Schaaf & Thompson, Virtual Prototyping enables to examine, manipulate, and test the form, fit, motion and human factors of conceptual designs. [14. p. 941] Early, and still valid definitions for terms *virtual prototype* and *virtual prototyping* are defined by Garcia, Gocke, and Johnson in reference [15]:

- ***Virtual Prototype:*** "A computer-based simulation of a system or subsystem with a degree of functional realism comparable to a physical prototype." [15, p.26.]
- ***Virtual Prototyping:*** "The process of using a virtual prototype, in lieu of physical prototype, for test and evaluation of specific characteristics of a candidate design." [15, p.26.]

Virtual Prototyping is used e.g. to investigate manipulator trajectories, joint values and potential collisions. Task Description (TD) which is performed in the Delmia environment can be described as Virtual Prototyping. TD includes all tasks for the manipulator and tools, and the process must be accomplished before development process advances. I.e. TD is a virtual verification tool. The main benefit that is achieved from TD is collision detection.

Potential Problem Analysis

The process can be examined against inhuman factors after the RH tasks are defined for the manipulator and tools. Potential Problem Analysis (PPA) is used to examine problems that have not yet happened. Extensive theory of PPA has been created by Kepner & Tregoe. [16] A simple example of the PPA is illustrated in Table 4.

Table 4: The example of PPA table [16]

Phase of Operation	Potential problem(s) foreseen	Cause(s) for problem(s)	Suggested solution(s) for problem(s)
Attach manipulator to tool	Manipulator cannot be connected to the tool	Manipulator interface is mechanically stuck	Return to depot and chance manipulator interface
		Tool interface is mechanically stuck	Take spare tool if it is usable
			Return to depot and chance functioning tools

PPA is a powerful tool to prevent and foresee problems that especially are caused by e.g. mechanical, electrical, and hydraulic failures. All potential problems from every phase of the process will be gathered in teamwork by brainstorming.

Operator Feedback

Operator Feedback (OF) is applied to test preliminary prototypes of development tools in real physical environment. Operational testing for the WHMAN has been on-going at the Test Stand. IHA3D environment allows real-time visual feedback from the manipulator. The trials for preliminary prototype tools produce observations that are necessary for the WHMAN operator, and thus required to achieve.

3.2 Engineering Design

Engineering Design phase can be described as a traditional engineering phase. In this phase all components and parts are designed “so that they fit together as an operating whole that meets the system operational requirements.” [10, p. 409.] These activities include designing of components and validation of designed components. Figure 17 illustrates the location of Engineering Design phase at system life cycle with main tasks, inputs, and outputs.

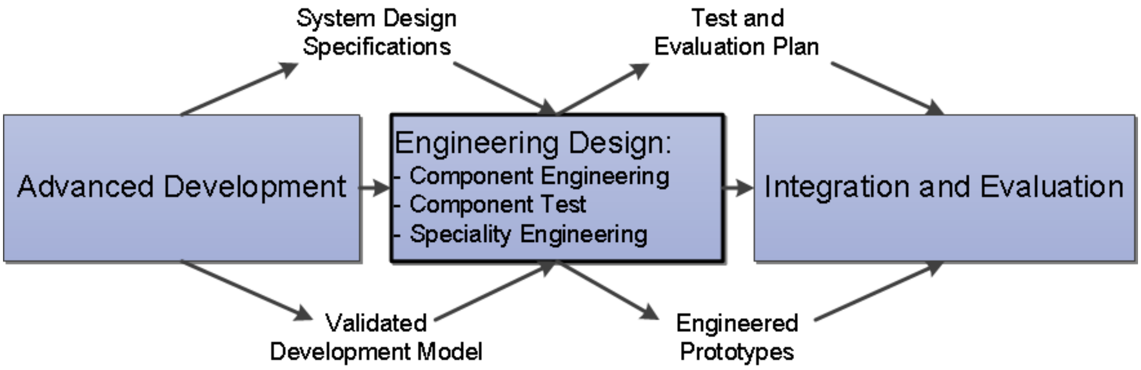

Figure 17: Engineering Design phase in a system life cycle [10]

The Systems Engineering theory that is delineated by Kossiakoff et al. has been utilized in this development process only for design validation. Design validation proceeds at various levels throughout the Engineering Development stage and in the Engineering Design phase it concentrates on validation of the physical implementation of the components. Design validation covers two types of tests at this phase: development testing and qualification testing. Development testing occurs during component design process and qualification testing ensures that final production design meets its specifications. Test planning is an important systems engineering contribution i.e. “to ensure that component features that were identified as potential risks are subjected to test to confirm their elimination or mitigation.” [10, p. 432.] Virtual verification must update after preliminary designs of the development object has been engineered.

3.2.1 Development Testing

In development testing the basic design of the component is validated. Especially components, that are highly stressed, newly developed or operated at levels beyond its specifications, require development testing. Collecting of failure statistics, by recording failures and identifying their source, is useful for reduce incipient failure at later development phases. [10, p. 433]

3.2.2 Qualification Testing

Qualification testing concerns to test interfaces of the unit so that it will fit exactly with its mating components. This can be accomplished by inserting the component under test into an environment in which it will operate as part of the total system. [10, p. 434-435]

3.3 System Integration and Evaluation

System Integration and Evaluation is the last phase before ready and working systems. In this phase all system elements are assembled to subsystems and systems. Assembled subsystems and systems are validated via testing. The results of tests are compared to system operational requirements and modifications are performed if it is necessary. Figure 18 illustrates the Integration and Evaluation phase defined by Kossiakoff et al.

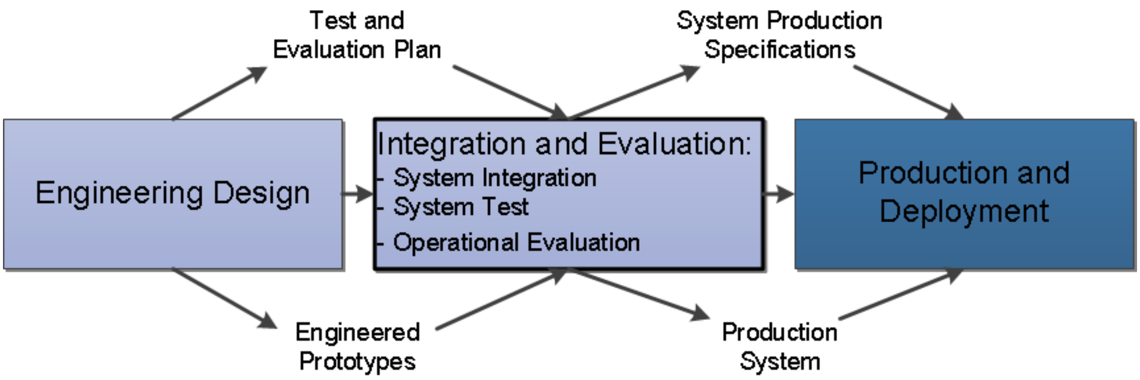

Figure 18: Integration and Evaluation phase in a system life cycle [10]

In Figure 18 Integration and Evaluation phase is presented as an independent phase. However, Integration and Evaluation phase is closely connected with previous Engineering Design phase. All deficiencies that will be discovered in the Integration and Evaluation phase are improved in the Engineering Design phase. Figure 19 illustrates the overlap of these two phases.

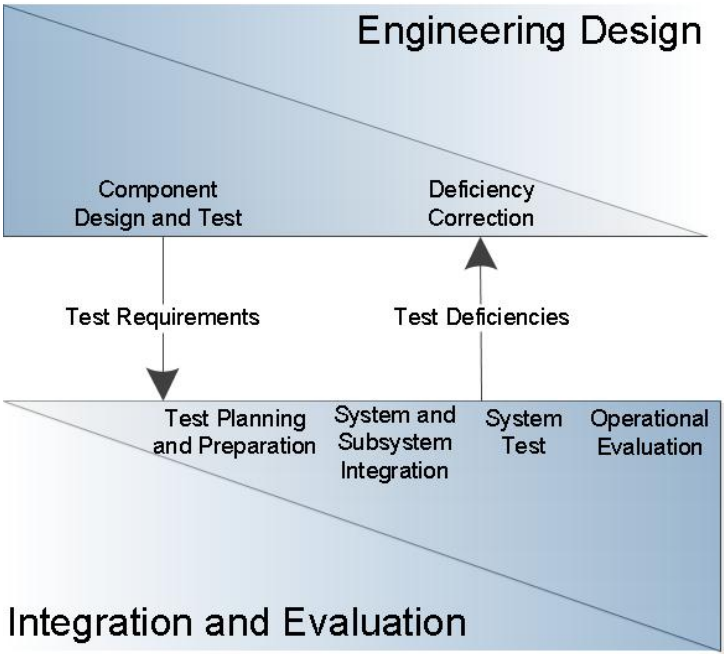

Figure 19: Relations between Engineering Design and Integration and Evaluation [10]

Following subsections concentrate on system integration, system developmental testing and operational test operations.

3.3.1 System Integration

System integration normally consists of two stages: first individual subsystems are integrated from the system elements and after that subsystems are assembled together into the total system. Between these two stages is essential to test individual subsystems to discover all deficiencies and discrepancies at subsystem level. After all subsystems are tested individually, system integration can proceed in an orderly i.e. subsystems are added one at a time and after that tests are performed again to ensure the correct behaviour of the integrated system. This technique may need lots of time depending on the system but it is cost-effective in the development of large systems, it enables control of process and it simplifies diagnosis of discrepancies. [10, p. 455]

Test Configuration

Integration tests that are performed after subsystems are assembled require versatile and readily reconfigurable facilities. Subsystem test configuration is illustrated in Figure 20.

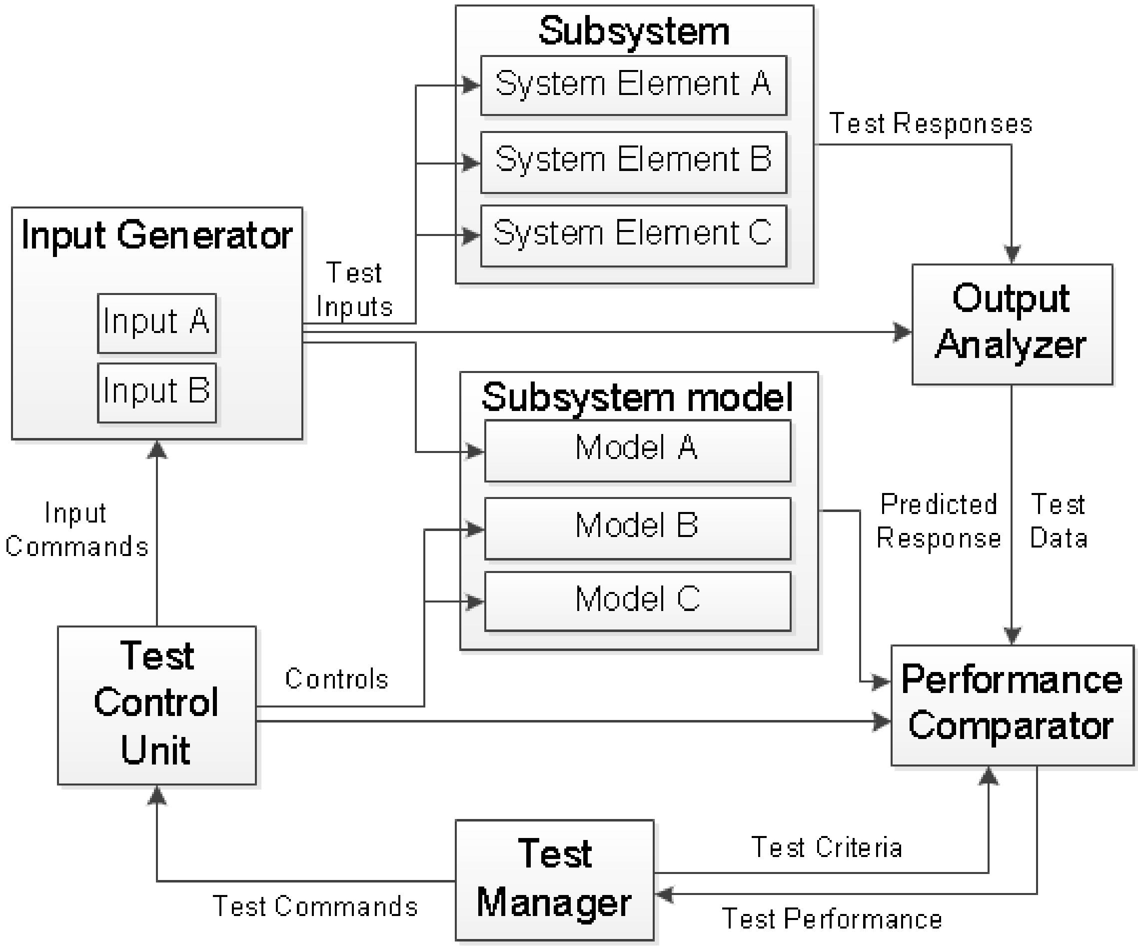

Figure 20: Subsystem test configuration [10]

The test configuration presented in Figure 20 is an example and it will be varied and simplified depending on the system under development. The explanations for the blocks illustrated at Figure 20 are [10, p. 456-457]:

- ***Subsystem and System Elements*** are the physical subsystem and components under test.
- ***Subsystem Model*** is the model of Subsystem. It may be exact replica of Subsystem, mathematical model of Subsystem or simple lookup table.
- ***Input Generator*** converts test commands into functional and physical commands for Subsystem and Subsystem Model.
- ***Output Analyzer*** converts unreadable outputs of Subsystem to quantitative form.
- ***Performance Comparator*** matches measured and predicted data together.
- ***Test Manager*** is the supervisor or operator of the testing.

3.3.2 Developmental System Testing

After every functions of components and subsystems have been ensured, the system may be tested as a unified whole. In developmental system testing stage the system is tested against its technical requirements. Technical requirements comprise of system specifications for performance, compatibility, reliability, maintainability, availability and safety. Developmental system testing can be considered as a rehearsal for the operational evaluation. [10, p. 462]

System Testing Objectives and Configuration

System developmental testing shall be situated as realistic environment as possible, because all significant issues should be resolved before operational evaluation. However the testing environment must be such that all discovered issues are easy to improve or repair, i.e. testing environment cannot be too hazard. Successful documentation from the deficiencies of the components and subsystems is essential for the developmental process, because they are the most common cause of a failure on this level testing. Failures on this level cause serious delays to development process and they must be resolved as soon as possible. The documentation of the deficiencies eases the traceability of failures on the lower levels. [10, p. 462]

According to Kossiakoff et al. system testing configuration is "designed to subject the system under test to all of the operational inputs and environmental conditions that it is practical to reproduce or simulate and to measure all of the significant responses and operating functions that the system is required to perform". [10, p. 463.] The most significant measurements are determined in system-level requirements and specifications. Kossiakoff et al. describes system level test configuration as follows [10, p. 463-464]:

- System Inputs and Environment:
    1. The test configuration must represent all conditions that affect the system's operation, including primary system inputs and the system interactions with its environment.
    2. As many of the system real conditions as practicable should be exact replicas of real environment. The conditions which are not practicable should be simulated to realistically represent their effect on the system.

3. The system real operational inputs that cannot be realized or simulate to the system test configuration (e.g. the gamma radiation of the fusion power plant) require special tests that carry out their functions and interactions with the system.

- System Outputs and Test Points:
    1. The system outputs that are used for assessing performance of system should be converted into measurable form and recorded during test period.
    2. The test inputs and environment conditions should also be recorded to enable correlations between inputs and outputs.
    3. Sufficient number of test points should be monitored to discern any deviation from the expected outputs.

Test Analysis and Discrepancies

Test Analysis comprises a detailed comparison of realized system performance (a function of test stimuli and environment) and predicted system performance. Any deviations between realized and predicted performance must launch a sequence of actions to resolve the source of discrepancy. Any discrepancies that are occurred at system level testing are due to:

1. a fault in test equipment
2. a test procedures
3. a test execution
4. a test analysis
5. the system under test
6. an excessively stringent performance requirement

Usually the discrepancy sources are traced to the first four causes and they need to be eliminated before any modifications will be made into the system. The fifth cause is the most serious cause: if the discrepancy is traced to the system under test the system engineer must decide the nature of the failure. The failure can be minor, serious, not understood or not serious. Depending on the nature of the failure, the further action is decided after the painstaking analysis of the failure by systems engineer. Some of the major discrepancies can be easily and quickly corrected but usually correction actions causes a cascade of changes in system design. [10, p. 466-467]

3.3.3 Operational Test and Evaluation

In this subsection main concentration is on the comparison between test results and the operational requirements. In previous subsection the comparison was between partially predicted test results and technical specifications. In the operational test and evaluation the main process is to focus on validation of the system instead of verification of requirements. It is supervised by customer or an independent test agent, test inspector. In this phase the developed system is subjected to series of tests that perform intended functions of the system in an environment which is identical or closely real with its operational environment. Prerequisite for system production is complete fulfilment of system operational requirements. [10, p. 467-468]

Test Objectivities

The main focus at this level is on operational requirements, mission effectiveness and user suitability. A preproduction prototype of the system, which all obvious deficiencies have been eliminated in the previous phases, is subjected to the operational tests. Suspension of operational tests may be caused if the prototype has still some significant faults. Prioritization of test objectivities is essential for operational test due to limited time and resources. Kossiakoff et al. defines a generally applicable list of high-priority areas for operational testing [10, p. 468]:

1. ***New Features:*** Usually new features are designed to eliminate deficiencies of the predecessor system. Thus they will affect greatest changes and greatest uncertainties to the system and they have the top priority for operational test.
2. ***Environmental Susceptibility:*** Operational test could be the first opportunity to observe the influence of the system real operational environmental.
3. ***Interoperability:*** The system compatibility and flexibility e.g. with external equipment and nonstandard communications protocols are essential to test if the system is connected with external systems or elements.
4. ***User Interfaces:*** Human-machine interfaces of the system must be determined, i.e. how the system operators employ the developed system.

Test Planning

Test plans should include the basic guides and procedures for conducting operational tests. Furthermore the plans should include special and follow-up actions or for earlier noticed deficiencies and problems. The realism of operational tests should be considered very closely when planning the tests because the realism of tests is directly proportional with costs and also validity of the tests. [10, p. 470]

Test Equipment and Facilities

In the operational tests only limited data is allowed to apply, i.e. all auxiliary subsystems, which perhaps were used in previous tests for easier fault discovering, shall be removed from the system. This is due to fact that the operational tests are performed for the ready prototype system in its real operating environment. However the system developer and designer may perform some auxiliary measurements or tests if there is a risk that some deficiencies may still discovered. This facilitates the traceability of single failure from the whole system. [10, p. 472]

Evaluation

The evaluation of the operational tests is carried out by the customer or the independent evaluation agent. The object of the test inspector is to validate that the system's performance meets its operational requirements, i.e. whether or not the system fulfils the needs of the customer. The test reporting comprises the final results of operational tests. Furthermore it can include e.g. recommendations for changes to eliminate any deficiencies identified during the development process or to improve system performance. [10, p. 474-475]

4 Advanced Development of CLS tools

The Advanced Development phase of CLS tools is presented in this chapter. Firstly Task Description is discussed about, after that Operator Feedback is presented and finally Potential Problem Analysis for SC locking process is presented. After that, the requirements that are developed from these operations or somewhere else at the development process are declared.

4.1 Starting point of Advanced Development

The first detailed preliminary Task Description has been studied by Marchand. [17] The preliminary TD has been accomplished with CLS tools that are presented in Figure 21. These tools are used as an initial point of the development process.

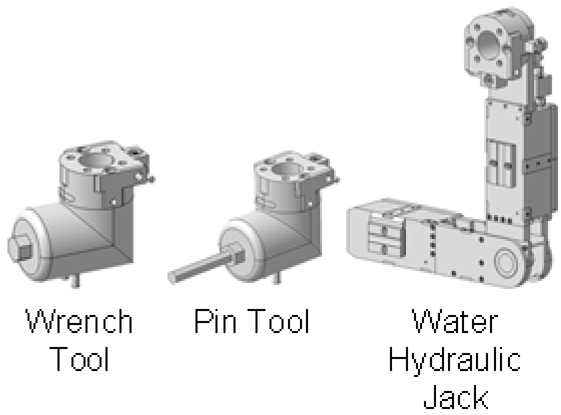

Figure 21: CLS tool models in the preliminary TD [17]

In Figure 21 Wrench Tool (WT) and Pin Tool (PT) are separate tools. These two tools are on the concept level. Water Hydraulic Jack is a prototype which cannot be operated remotely.

4.2 Operator Feedback

The models of WT and PT presented before are on the concept level. This does not mean just that they aren't manufactured but also their driving mechanisms of Allen keys haven't decided. It has been noticed that by combining these two tools into one body, one U-support is reserved for further usage. In Figure 22 is presented the first prototype of combined Wrench-Pin Tool (WPT) that is used for the operational feedback.

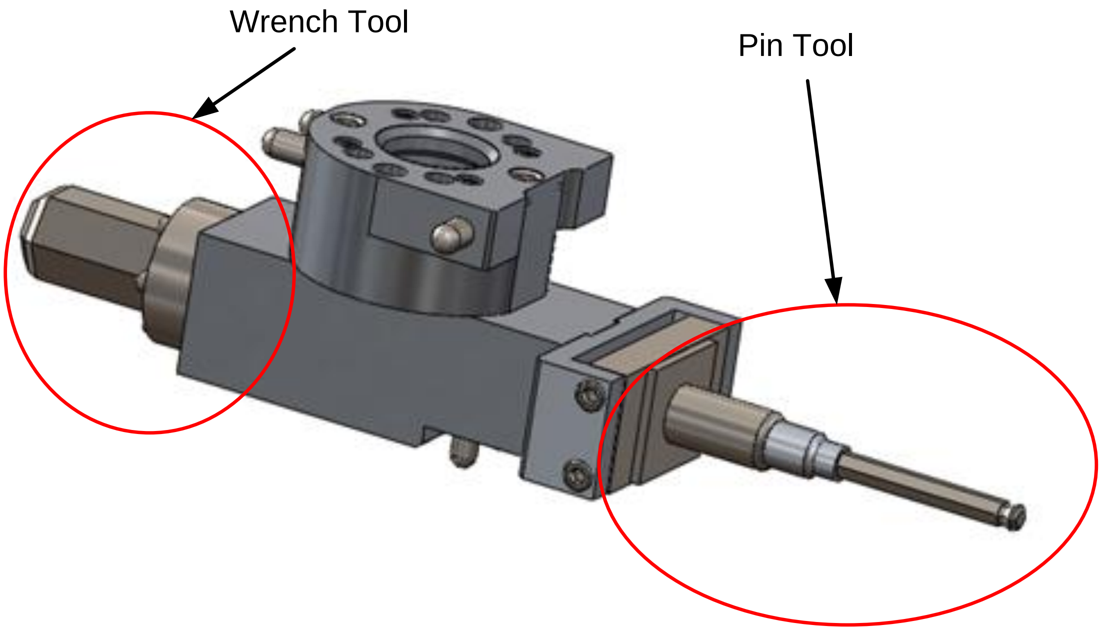

Figure 22: The first Prototype of combined Wrench-Pin Tool (WPT)

Water Hydraulic Jack (WHJ) has been manufactured and the model, shown in the Figure 23, is used for the operator feedback.

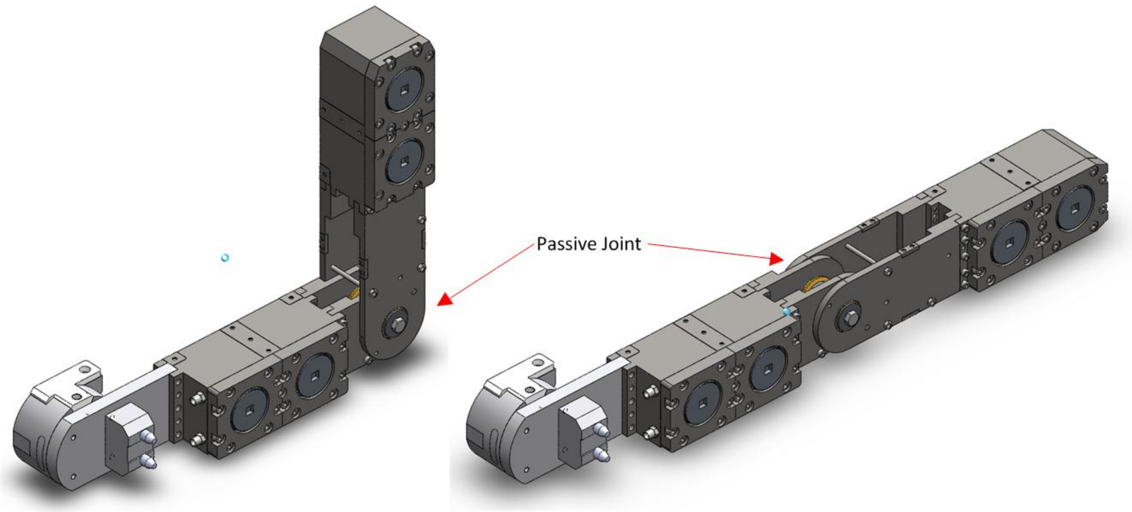

Figure 23: The first prototype of RH WHJ

Operator feedback has been reported earlier in the official document (reference [18]). Operational Feedback has been carried out at the DTP2 facility. This testing has been done on the Test Stand in order to not disturb concurrent Cassette Multifunctional Mover (CMM) testing that is being done on the Divertor Rail Mock-Up (DRM). During this testing, some observations have been made regarding the tooling used to practice CLS operations with. The tools that have been used are the first prototypes of WPT (see Figure 22) and WHJ (see Figure 23).

The WHJ has a passive rotational joint in the middle of it. This passive joint is designed to be stiff enough so that the WHJ's own mass is not enough to rotate the joint, but loose enough so that it can be forced to rotate inside the CLS slot when applying moderate force with WHMAN.

The main observation made about the current WHJ tool was that there is no electrical feedback of the passive joint's angle. This effectively prevents relying solely on virtual reality models for visual feedback when installing the WHJ into the CLS slot. This is because the position of a point on the end surface of the WHJ is a function of the passive joint's angle, and this angle is currently unknown. An illustration of this can be seen in Figure 24 (virtual model of the WHJ near the CLS mock-up's slot). The passive joint's angle in the left- and right hand side pictures is 90 and 80 degrees, respectively. The installation procedure was, however, successfully completed by using cameras to provide the needed visual feedback. [18]

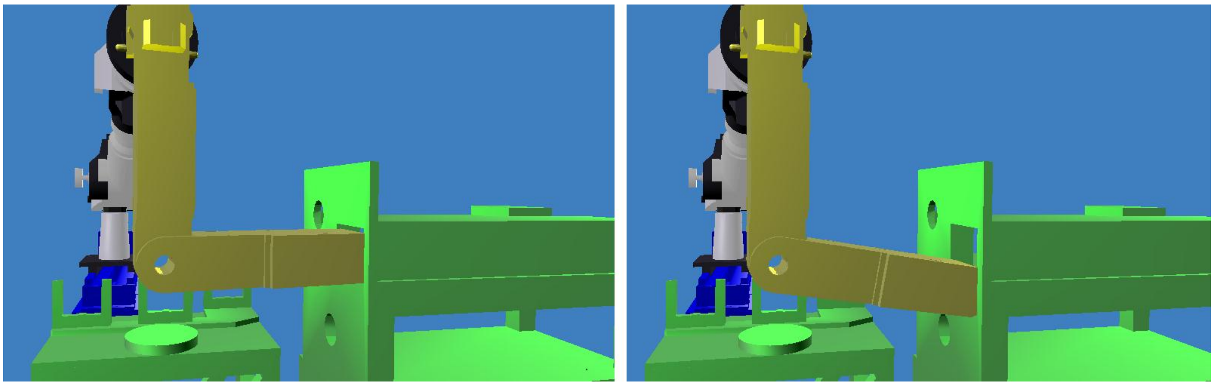

Figure 24: Visual feedback from IHA3D environment [18]

Another observation, from tests done with Gradel Cassette, is the accuracy of installation depth of WHJ to the Cassette slot. To position WHJ pushing plates to Cassette latches, WHJ should be installed to the slot with an accuracy of ~3mm, which would be hard to execute via RH (see Figure 25). If WHJ isn't installed to correct depth to the slot, pushing plates would take contact with cassette body and cause damage during compression. [18]

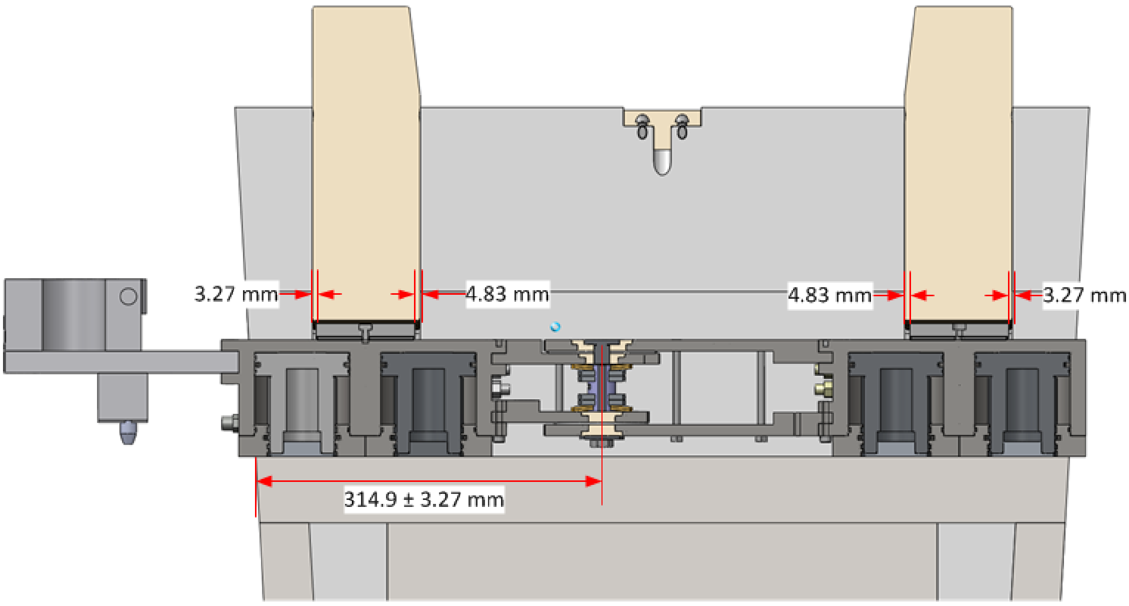

Figure 25: Optimal mounting depth and required mounting tolerance for RH WHJ [18]

Some observations were also made of the second tool used during the tests, the first prototype of WTP. In the tool mock-up (Figure 22) PT's Allen key was attached at ratchet spanner and wrench mechanism was used with simple wrench dowel, which was attached at the other end of tool mock-up. [18]

Operations with the WT were successful, however for some situations it could be beneficial to have a clear way to visually identify that the wrench dowel is installed at the correct depth, before or during the turning of the CLS latch. Operations with the PT were not successful and the following observations were made [18]:

The surface of the bolt, onto which the PT needs to be attached to, is very difficult to view with cameras. Visual inspection is difficult due to fact that the bolt's surface is "inside" the cassette (see Figure 26) and only visible through a cylindrical opening, the view to which is blocked by WHMAN during this operation. Pin Tool reliable alignment via RH is difficult especially since on the Test Stand's CLS mock-up, the moving pin itself is not present and so it is possible to miss and go past the bolt's surface with the PT. [18]

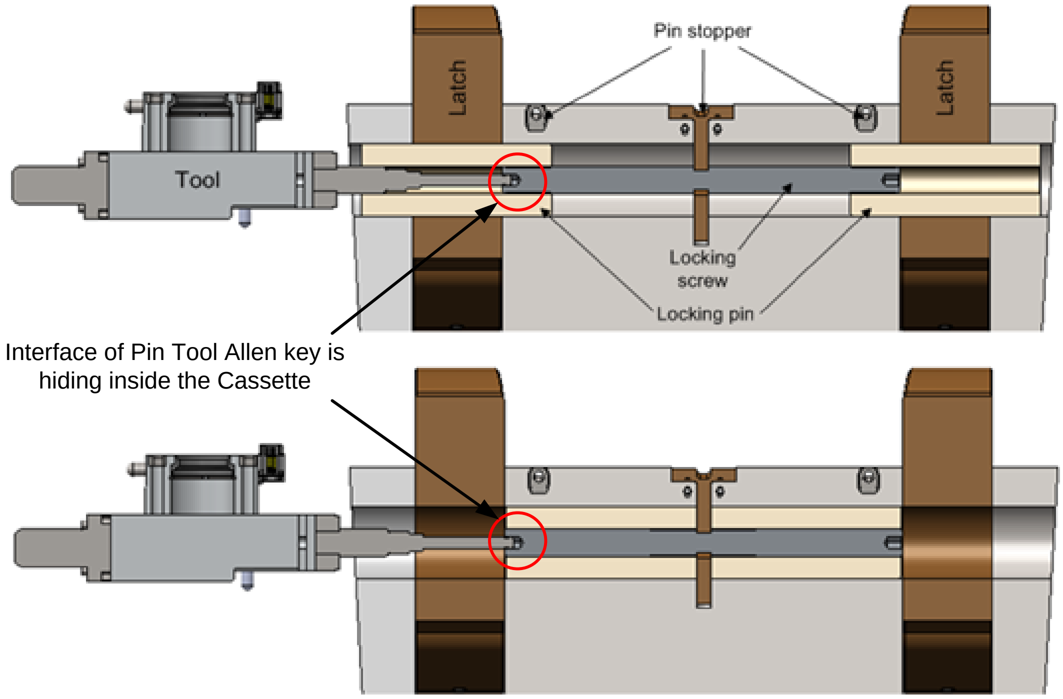

Figure 26: Pin Tool inserted into Pin Slot [18]

Requirements that are elicited from Operator Feedback for each tool are collected and presented in chapter 4.4.

4.3 Potential Problem Analysis for Divertor cassette Locking

Table 5 presents the Potential Problem Analysis for Second cassette Procedure. Requirements that are developed from PPA for each tool are collected and presented in chapter 4.4.

Table 5: Potential Problem Analysis for Second Cassette Locking procedure [18]

Phase of Operation	Potential problem(s) foreseen	Cause(s) for problem(s)	Suggested solution(s) for problem(s)
Insert WHJ into the compression slot	WHJ cannot be inserted into the compression slot	WHJ pistons are extended	Retract the WHJ pistons (Hydraulic Control)
Pressurize the WHJ	WHJ cannot pressurize	Hydraulic connector broken	Return to Hot Cell to acquire a new, functional WHJ
		Electric connector broken (valves cannot be operated)	
		WHJ hydraulics broken	
Detach WHMAN from pressurized WHJ	Cylinders cannot be locked	Locking valve cannot close (mechanical problem)	Un-pressurize WHJ, retract cylinders and return to Hot Cell to acquire a new, functional WHJ
	Quick connectors cannot be un-pressurized		
Operate cassette locking pin	Pin cannot be operated	Tool malfunction	Return to Hot Cell to acquire a new, functional tool
		Locking pin is mechanically stuck	Switch to emergency recovery tool (high torque) and force the pin
		Pin head is deformed to inoperable state	???
Attach WHMAN to pressurized WHJ	WHMAN cannot be connected to the WHJ	WHJ connector is pressurized (lock valve failure)	Operate emergency valve to release pressure from the WHJ cylinders
		WHJ connector is pressurized (leakage through WHJ piston seals)	
Un-pressurize the WHJ	WHJ cannot be unpressurized	Electric connector broken (valves cannot be operated)	Detach WHMAN from WHJ and physically operate the emergency valve after which the WHMAN can be re-attached to WHJ and the cylinder retracted (spring return)
		Hydraulic failure (valve broken)	
		Hydraulic connector broken	Detach WHMAN from the WHJ and sever a hose from the WHJ, thus releasing the pressure medium to the VV floor
Remove the WHJ from the compression slot	WHJ cannot be removed from the compression slot	WHJ cylinders remain extended	Drive the WHJ cylinders in retracted position
		WHJ stuck to the cassette structure	Apply more force

4.4 RH requirements for CLS tools

All Remote Handling requirements for Second Cassette Locking tools that are elicited from previous activity, or that have been arise during development process are presented in this section. Comprehensive list of all other requirements for the WHJ is presented in reference [8] and for WPT in reference [18]. RH Requirements for CLS tools are represented in Table 6, Table 7, and Table 8 for WHJ, WT, and PT respectively. These requirements can be considered as technical specifications of CLS tools. Operational requirements of CLS tools are:

- ***WHJ:*** Water Hydraulic Jack shall provide the mechanism to compress the SC.
- ***WT:*** Wrench Tool shall provide the driving mechanism to rotate CLS latches.
- ***PT:*** Pin Tool shall provide the driving mechanism to operate SC locking mechanism to lock and unlock SC latches.

Table 6: New Requirements for Water Hydraulic Jack

Req. Id.	Requirement description	Source	Priority M/P/O	Remarks/ Nominal Condition
RHD-WHJ1	Information of WHJ passive joint angle shall be provided to the operator	Operator Feedback	M	N/A
RHD-WHJ2	Indication of the WHJ correct mounting depth to WHJ slot shall be provided to the operator	Operator Feedback	M	N/A
RHD-WHJ3	WHJ hydraulic cylinders shall be operated remotely	Task Description	M	N/A
RHD-WHJ4	WHJ shall withstand the load affected by compression of cassette without connection to manipulator	Task Description	M	N/A
RHD-WHJ5	Hydraulic quick connectors shall be attached without pressure	Manufacturer	M	N/A
RHD-WHJ6	Working pressure of WHJ shall be controlled	Operator Feedback	M	~110 bar
RHD-WHJ7	Indication of pressure reduction shall be provided to the operator	Operator Feedback	M	N/A
RHD-WHJ8	WHJ pistons shall be retracted to the folded position in case of a hydraulic or an electric failure	Potential Problem Analysis	M	N/A
RHD-WHJ9	WHJ dimensions shall be such that collisions between WHMAN/WHJ and DRM are avoided	Task Description	M	N/A

Table 7: New Requirements for Wrench Tool

Req. Id.	Requirement description	Source	Priority M/P/O	Remarks/ Nominal Condition
RHD-WT1	Indication of the correct mounting depth shall be provided to operator	Operator Feedback	M	N/A
RHD-WT2	Wrench tool shall provide means for reliable alignment into wrench slot double hex socket.	Operator Feedback	M	N/A

Table 8: New Requirements for Pin Tool

Req. Id.	Requirement description	Source	Priority M/P/O	Remarks/ Nominal Condition
RHD-PT1	Locking screw's ends of motion shall be detected and jamming avoided.	Potential Problem Analysis	M	N/A
RHD-PT2	Pin tool Allen key shall reach at SC locking screw's hex socket.	Operator Feedback	M	N/A
RHD-PT3	Pin tool shall provide means for Al-len key's reliable alignment into SC locking screw hex socket.	Operator Feedback	M	N/A
RHD-PT4	Current position of locking pins shall be measurable.	Operator Feedback	M	N/A
RHD-PT5	Measured value of locking pins posi-tion shall be absolute value for case of power failures.	Potential Problem Analysis	M	N/A
RHD-PT6	In case of SC locking mechanism jamming, there shall be back-up sys-tem to open the jam.	Potential Problem Analysis	M	N/A

5 Engineering Design of CLS tools

This chapter concentrates on Engineering Design phase for Divertor Cassette Locking Tools. The designs of developed tools are first briefly presented, and after that development and qualification testing are performed for certain components and interfaces of the tools. Last section presents results of visual verification of Cassette Locking Process. Comprehensive designing process of the tools has been made in the official ITER document. [18]

5.1 Engineered Water Hydraulic Jack

The initial WHJ and the final state of the modified WHJ are presented in the Figure 27. Hydraulics, angle sensor and interface modifications are briefly represented in the following subsections.

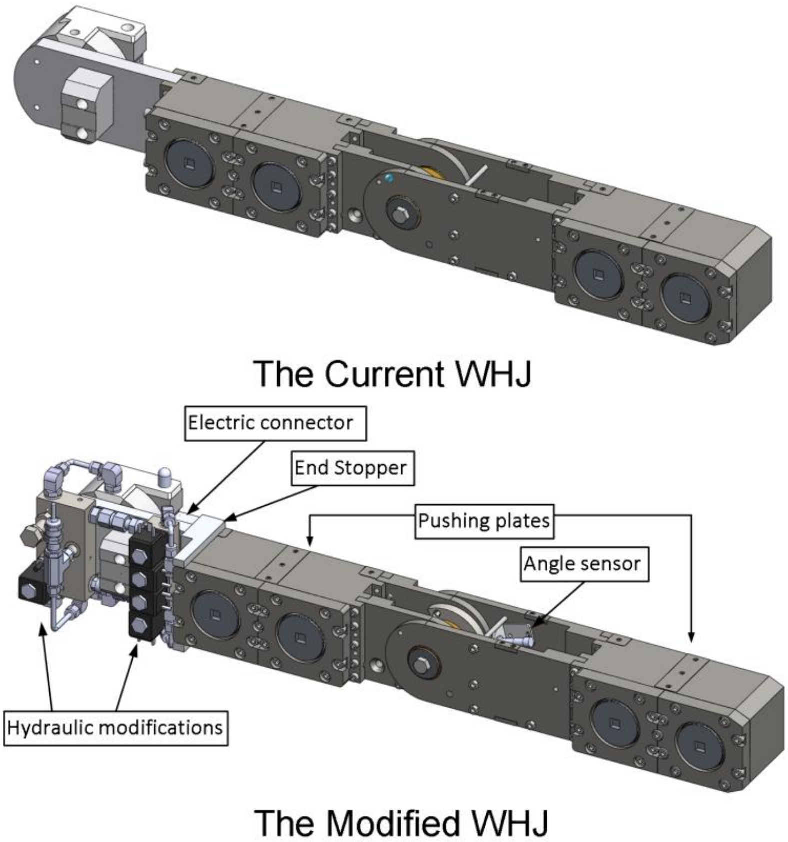

Figure 27: Differences between the original and the modified WHJ [18]

5.1.1 Hydraulics

Sole hydraulic components that were in the original WHJ were two hydraulic quick connectors, four hydraulic cylinders and hoses between cylinder blocks. New requirements (RHD-WHJ3, RHD-WHJ4, RHD-WHJ5, RHD-WHJ6, RHD-WHJ7 and RHD-WHJ8) define that the WHJ shall be RH compatible and connection/disconnection between WHMAN tool exchanger and WHJ interface shall be attached unpressurized due to the requirements of the quick connector's manufacturer. These requirements create the most significant modifications to the WHJ. Furthermore, hydraulic modifications, i.e. all hydraulic valves, pipes and fittings, shall not exceed certain space limits which difficult the design process more. RH capable hydraulic schema for WHJ is presented in Figure 28. [18]

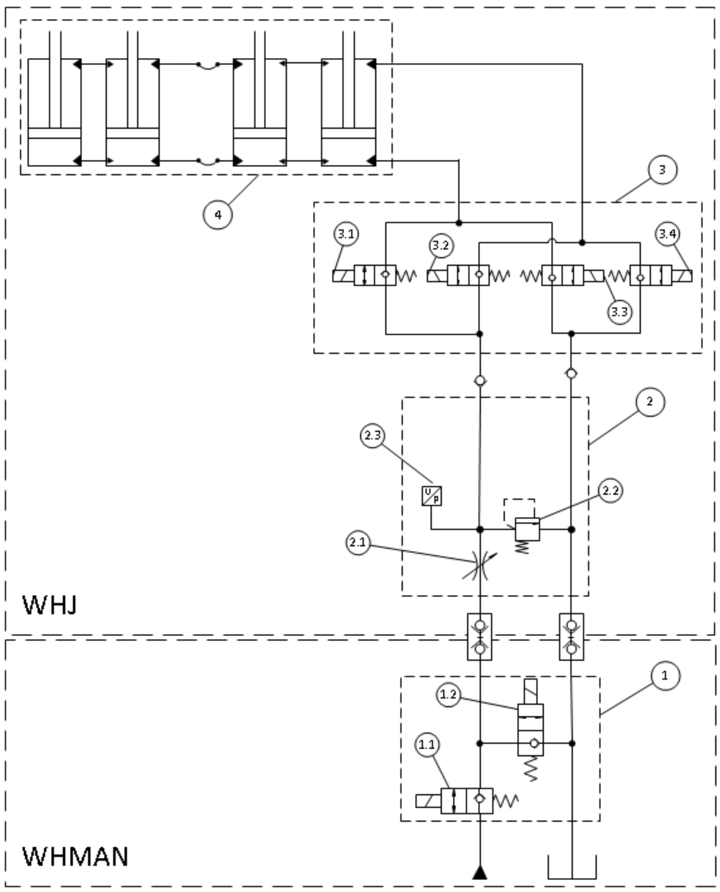

Figure 28: Hydraulic schema of the Modified Water Hydraulic Jack [18]

Here are explained hydraulic components that are shown in Figure 28.

- ***Block #1:*** Depressurization at WHMAN side
  - Component #1.1: Blocks pressure line
  - Component #1.2: Connects pressure side quick connector to tank line when WHMAN is not connected to WHJ
- ***Block #2:*** Pressure reduction at WHJ side
  - Component #2.1: Restricts flow so that pressure before flow control valve (i.e. in WHMAN) stays at 210 bar
  - Component #2.2: Reliefs the WHJ pressure to the designed set value
  - Component #2.3: Verifies the pressure reduction
- ***Block #3:*** WHJ control block
  - Components: 4 pieces On/Off valves that control movement of the WHJ pistons
- ***Block #4:*** WHJ Cylinder blocks

5.1.2 Angle Sensor

Information of WHJ passive joint angle shall be provided to the operator (RHD-WHJ1) because RH operations of the WHJ are less robust and reliable if the angle of WHJ passive is unknown. During folding/ unfolding process of WHJ a tip of WHJ can translate and also rotate slightly inside of the WHJ slot (see Figure 29). Thus position of the tip is non-specific due to the unknown angle of passive joint. This can lead to over bending of the WHJ when it’s unfolded or folded. [18]

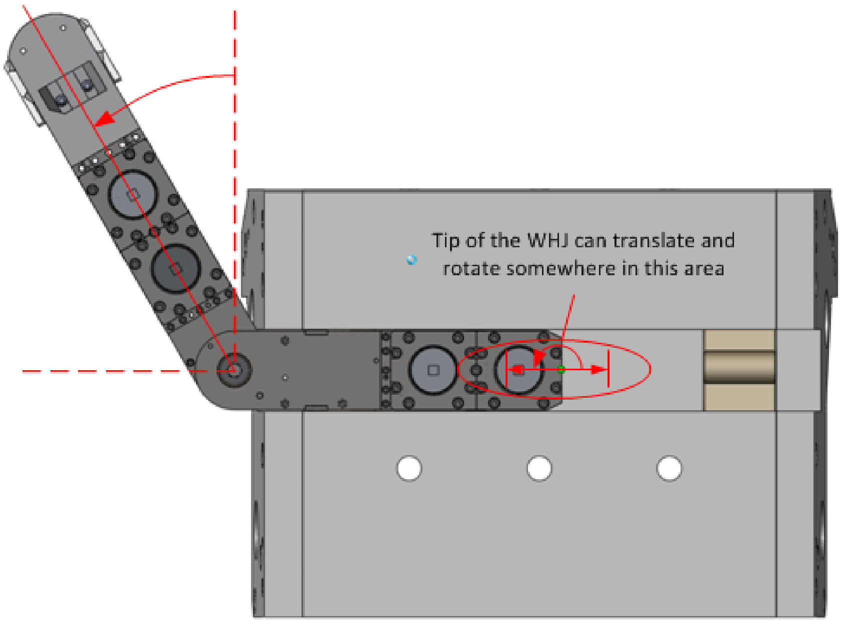

Figure 29: The position of the WHJ tip during WHJ unfolding process [18]

Angle sensor shall be very compact, because it must fit into the WHJ body, i.e. between the WHJ side plates, and the sensor shall not disturb the movements of the hydraulic hoses during WHJ folding/ unfolding. An inductive proximity sensor with adjustable measuring plate (see Figure 30) can be installed between the plates and the hoses are free to move.

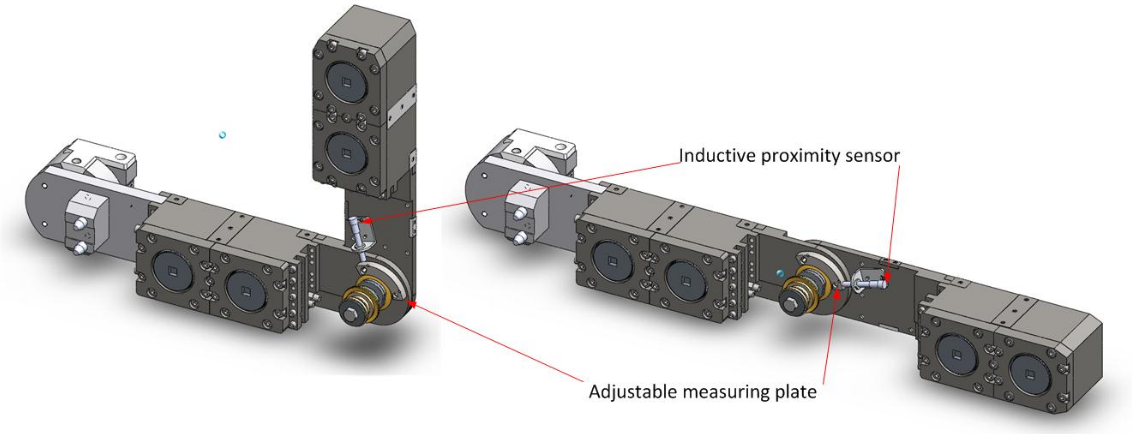

Figure 30: Angle sensor for WHJ passive joint [18]

The inductive proximity sensor is made by Sick and it is capable to read distances between 0 mm and 4 mm from stainless steel (AISI 316). [19]

5.1.3 Interface modifications

Indication of the WHJ correct mounting depth and alignment shall be provided to the operator (RHD-WHJ2) i.e. pushing plates of WHJ shall be aligned precisely with the SC latches. The WHJ can incur serious damage to itself and the SC during compression if the pushing plates aren’t exactly at same depth with latches. Figure 31 illustrates the contact geometries (width of pushing plates and SC latches) of the current design. In the current design does not exist any mechanism to ensure the correct mounting depth of WHJ. The correct depth is the most important Degree of Freedom (DoF) to be ensured. [18]

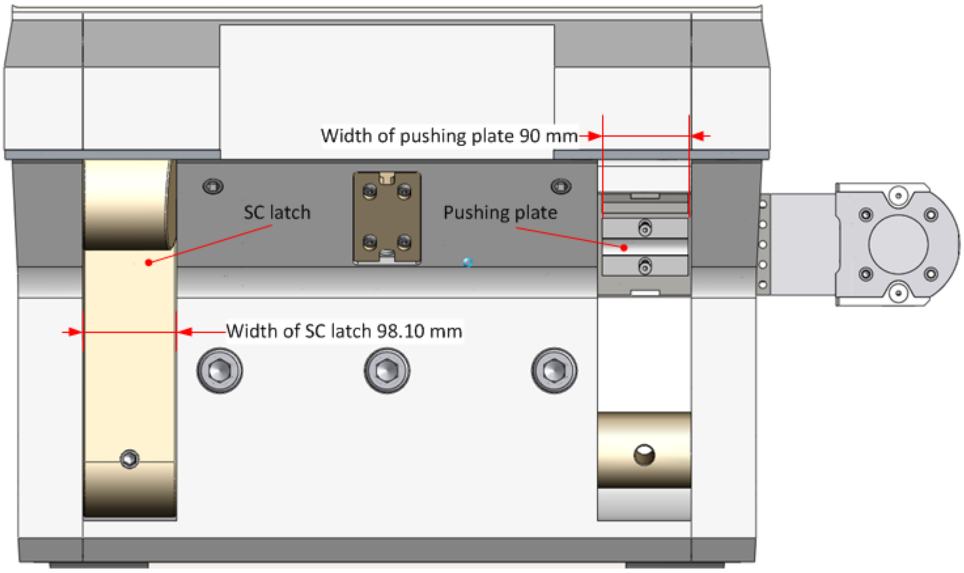

Figure 31: Contact geometries between SC and WHJ [18]

The required mounting tolerance of WHJ is fractional compared to the total length of WHJ due to the geometries of the SC latches and pushing plates (shown in Figure 31). The optimal mounting depth (314.9 mm measured from the Cassette side plate) and the required mounting tolerance of WHJ (±3.27 mm) are represented earlier in Figure 25. Secondly, depth verification for operator is difficult due to 3.33° CLS side-plate misalignment vs. WHJ slot which is shown in Figure 32. [18]

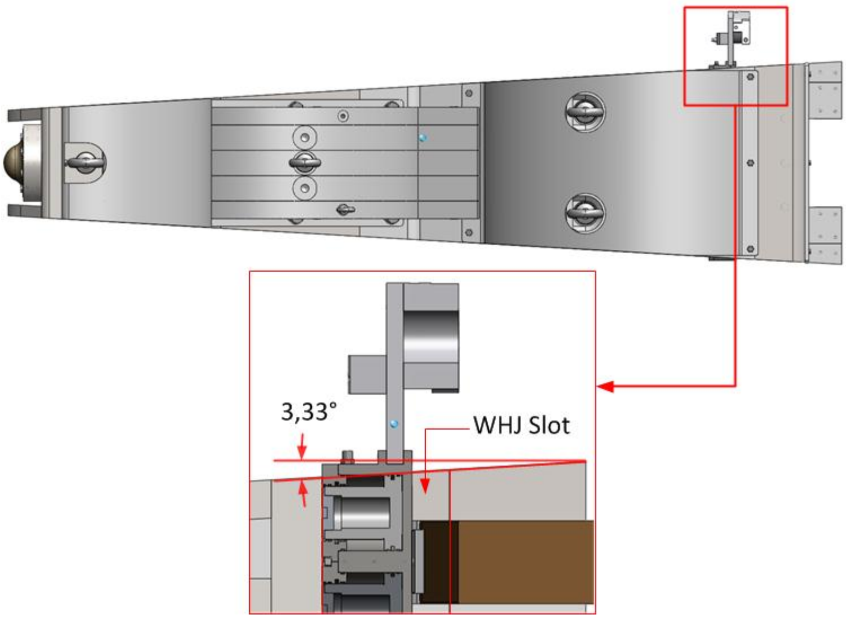

Figure 32: 3.33 degree misalignment of the SC side plate [18]

Pushing plate width reduction

The required mounting tolerance can be easily improved by width reduction of WHJ pushing plates (see Figure 33 and Figure 34).

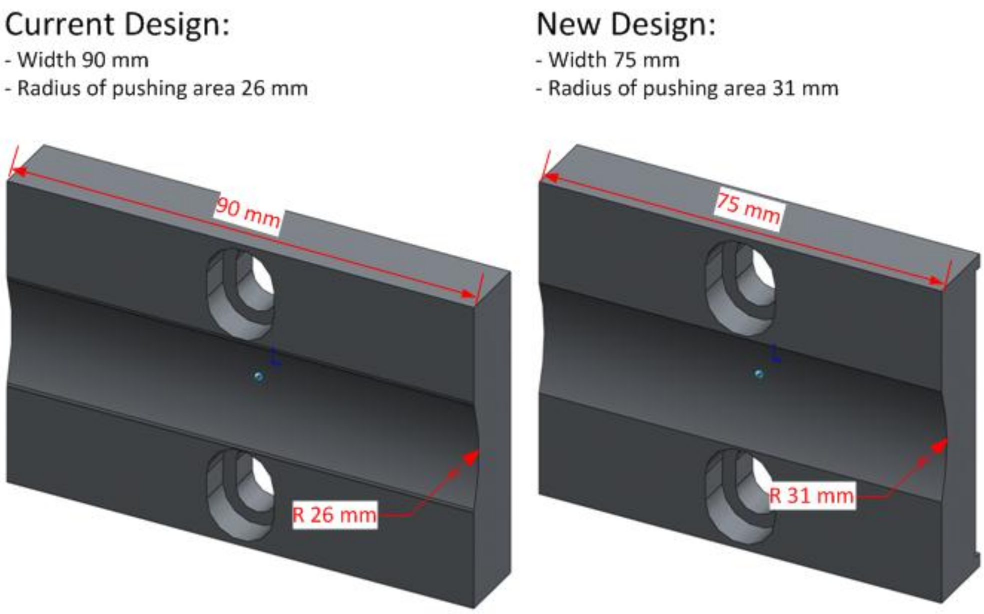

Figure 33: WHJ pushing plate modification [18]

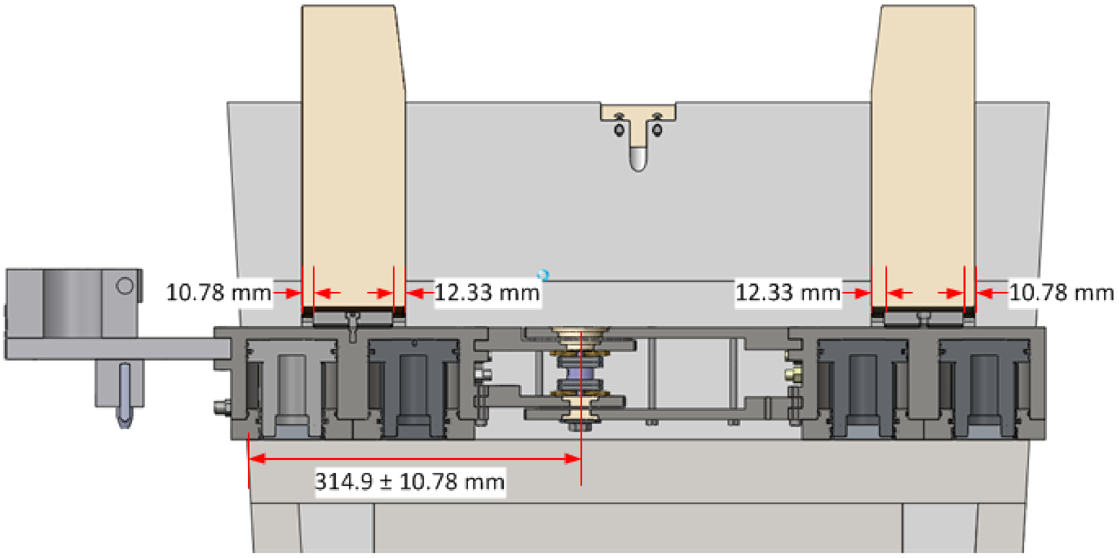

Figure 34: Improved mounting tolerance with modified pushing plates [18]

Required mounting tolerance has increased from 3.3 mm to 10.8 mm with the assistance of pushing plate width reduction. The function of pushing plates is to transmit and distribute the compression force of WHJ to the SC latches. Due to these modifications, contact pressure between pushing plates and latches was studied again (Appendix 1).

WHJ End Stopper

WHJ end stopper enables the indication of WHJ correct mounting depth to the operator. In the current design does not exist any mechanism which ensures the correct mounting depth of WHJ thus it can be easily pushed too far. Furthermore, in the current SC design the CLS side-plate is not perpendicular with the WHJ slot (3.33° misalignment see Figure 32). Due to this misalignment the mounting depth of the WHJ is inaccurate to measure and difficult to ensure. Cassette side plate can be used for the end Stopper, but small area near the around the WHJ slot must be machined perpendicular with the WHJ slot, because the misalignment causes WHJ sliding to its longitudinal direction during compression process (see Figure 35). In Figure 36 is presented the WHJ end stopper and perpendicular area with its slot. [18]

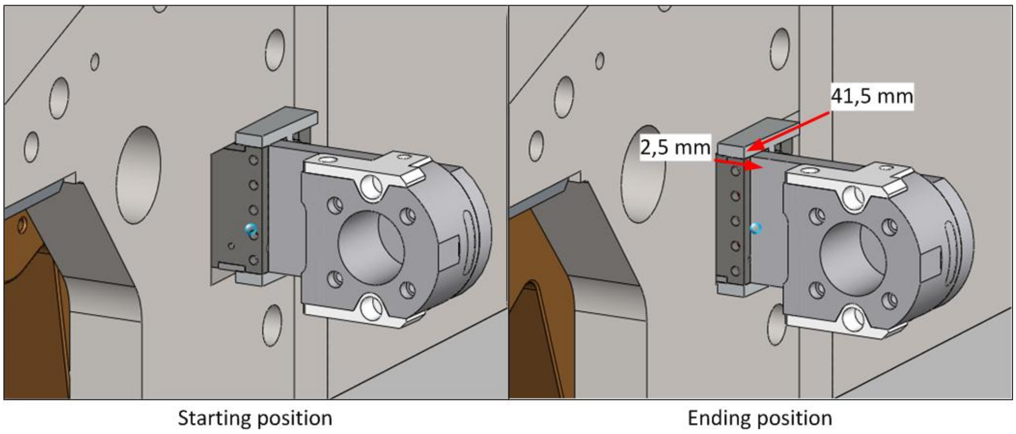

Figure 35: WHJ movement during compression process [18]

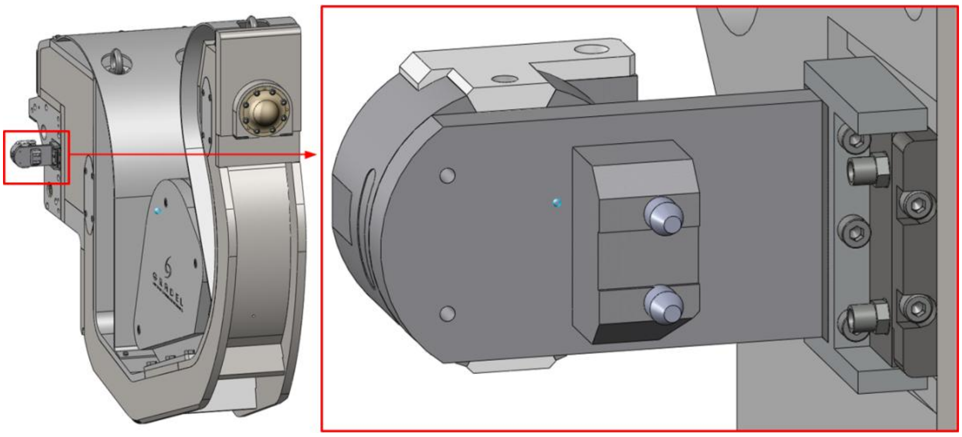

Figure 36: WHJ End Stopper [18]

5.2 Testing of WHJ

In this section development testing and qualification testing are performed for WHJ.

5.2.1 Development Testing

Development testing results for WHJ, are gathered into Table 9.

Table 9: Development testing of WHJ

Component	Testing reason	Testing against	Testing method	Result	Fault/ Remarks
Flo Control 2/2 valves	High operational pressure	External leakage	Static pressure	Pass	-
		Internal leakage	Static pressure	Partly pass/ fail	Variability at sealing face of valves
Swagelok pressure relief valve	Unproven technology	Function	Static pressure	Pass	-
Bis Valves Throttle valve	Unproven technology	Function	Static pressure	Fail (repairable)	Cavitation erosion at needle
SICK inductive proximity sensor	Unproven technology	Function	Test bench	Pass	-

Results of development testing describe that Flo Control On/Off valves require careful addition tests against of internal leakage. Source of the Flo Control valves was digital hydraulic block that has 4 times 6 On/Off valves. Internal leakage tests were performed for every valve of the digital hydraulic block. Test arrangement is presented at Figure 37.

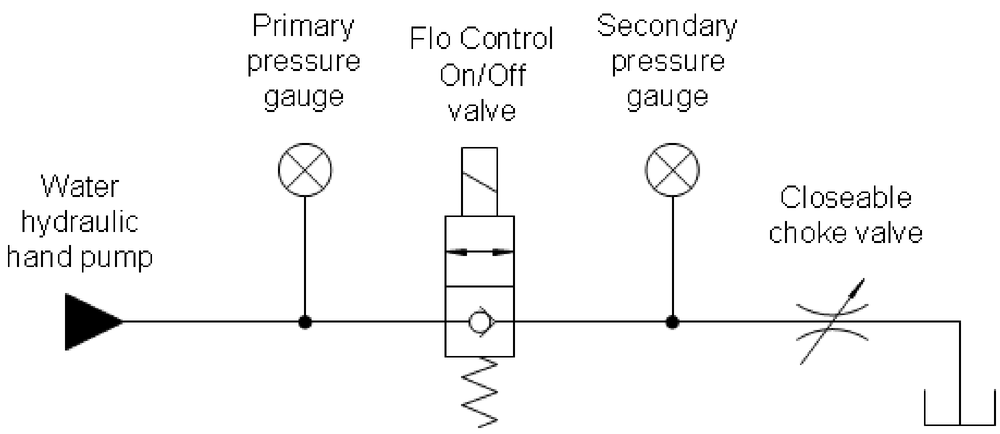

Figure 37: Internal leakage test arrangement for Flo Control On/Off valves

Internal leakage can be noticed if pressure rises at secondary pressure gauge, when choke valve is closed. The valves have extremely different sealing characteristics in spite of the type of valves (poppet valves). This could be caused by previous usage of digital hydraulic block and wearing of valves. Valves were ranked by their sealing characteristics and the best valves were selected for the system.

Another attention from development testing was the cavitation erosion at the needle of throttle valve. This can be arranged by modification of the cavity of the valve.

5.2.2 Qualification testing

Table 10 illustrates qualification testing results of WHJ interfaces.

Table 10: Qualification testing results for WHJ

Interface (WHJ/WPT)	Testing reason	Testing against	Testing method	Result	Fault/ Remarks
End-stopper – Jack slot	New interface	Compatibility	CAD	Pass	-
			Mock-Up	Not tested	Mounting depth against cassette shall be tested
Pushing plates – Cassette latches	Modification	Compatibility	Mock-Up	Not tested	Pushing plates compatibility with Cassette shall be tested
		Durability	FEA	Pass	Durability shall be tested in real environment

Results of qualification testing represent that WHJ End Stopper and Pushing Plates shall be tested in real environment. These tests could be performed at later phase of development process after the WHJ is integrated into its operating environment.

5.3 Engineered Wrench-Pin Tool

The model of the developed tool is represented in Figure 38. Two Allen keys are integrated into the one tool body which is called WPT: bigger (Wrench Tool) for Wrench slot and smaller (Pin Tool) for Pin slot. Wrench Tool is used by manipulator and Pin

Tool is used by an electric motor that has been installed into the tool body. Brief presentations of WPT main components are in the following subsections.

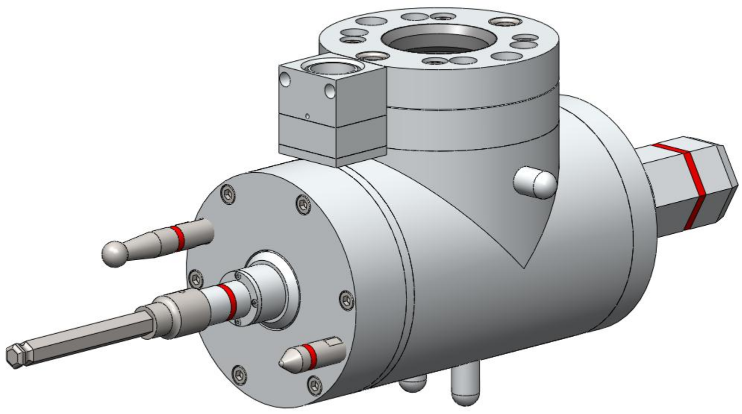

Figure 38: Developed Wrench-Pin Tool [18]

5.3.1 Rotating system of PT

Allen key of Pin Tool is rotated by an electric motor (see Figure 39). A planetary gearbox has integrated into the electric motor in order to produce required torque. An optical encoder has been integrated at the other end of the motor in order to resolve the movement of SC pins (RHD-PT1, RHD-PT4 and RHD-PT5).

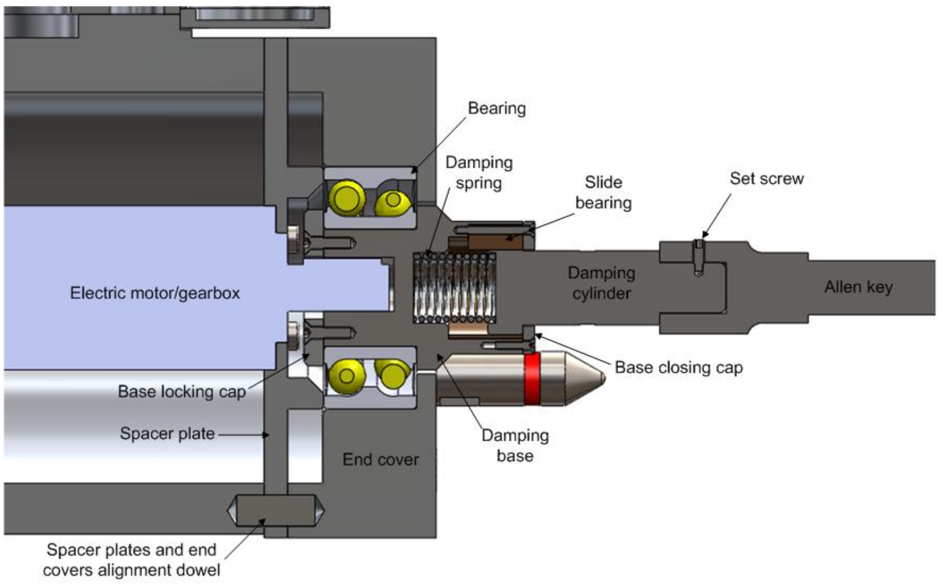

Figure 39: Rotating system of PT [18]

A gearbox output shaft is coupled to damping system. Damping system consists of damping base, damping spring, damping cylinder, slide bearing, base locking cap and base closing cap (see Figure 40). Primary function of damping system is to help alignment of Allen key into locking screw hex socket. When the Allen key is aligned in hex socket such an angle that sides of Allen key and hex socket are not parallel, the damping systems spring retracts. Because of damping spring, Allen key slips into hex socket when Allen key is turned and correct angle is attained. Secondary function of damping system is to absorb impacts which possibly directs towards pin tool and its rotating system for example in case of misalignment. Damping system together with bearing protects tool and electric motor for impacts for example in case of misalignment. [18]

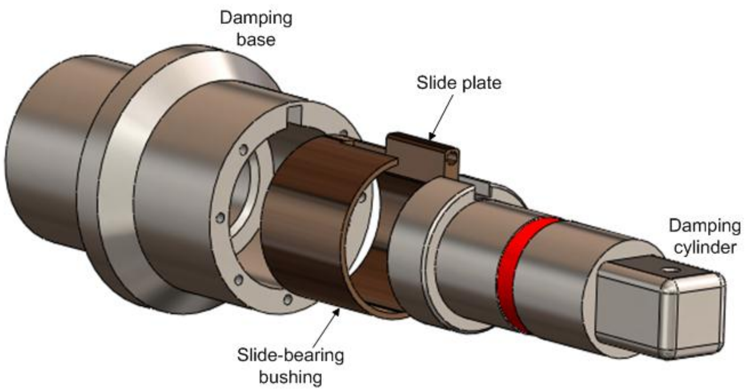

Figure 40: Damping system of PT [18]

5.3.2 Alignment system of PT

Due to RH requirements of PT (RHD-PT2 and RHD-PT3), the reliable and robust alignment of PT into cassette is needed. Alignment of tool is arranged by two Guiding Pins. The Guiding Pins are used to reduce the initial misalignment to bring pins within their capture range which themselves provides accurate final location. Alignment of tool is arranged in accordance with official ITER Remote Handling Code of Practice document. [20] Used method of alignment was generic ball-ended pin arrangement. This design incorporates a long ball-ended pin that locates in a circular hole and a short parallel pin that locates in a short slot. It is clear that described alignment arrangement requires some modifications into SC CLS side panels. [18] Insertion process shall be verified via inspection camera in order to realise robust insertion of PT. A clear visibility of PT Guide Pins during insertion process is prevented due to the misalignment of cassette side plate and modifications shall be done before Guide Pins can be tested and insertion verified. (Figure 42).

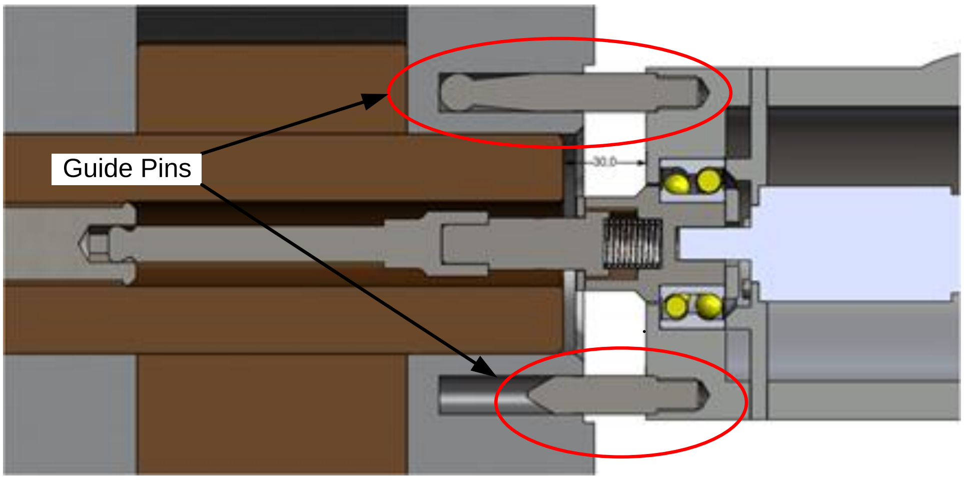

Figure 41: Alignment system of PT [18]

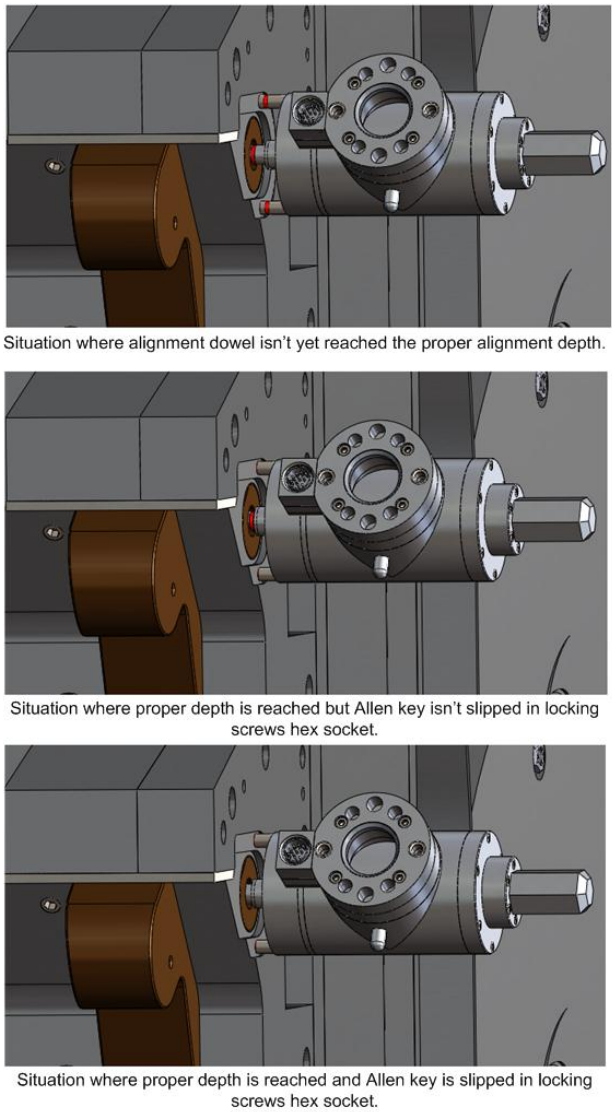

Figure 42: Visual inspection of PT insertion process [18]

5.3.3 Rotating system of WT

The Wrench Tool is used to rotate SC latches. Rotation movement is caused by WHMAN arm hence WT doesn't require additional rotating systems (see Figure 43).

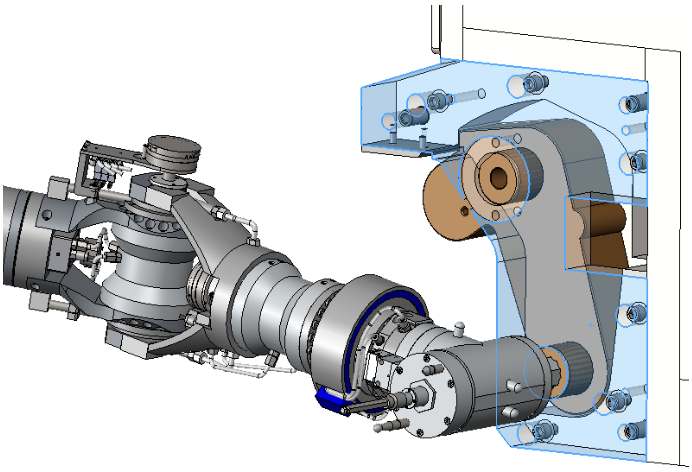

Figure 43: SC latches turning with WT and WHMAN [18]

5.3.4 Alignment system of WT

Alignment of WT into wrench slot will be done through inspection camera (RHD-WT1, RHD-WT2). For a help wrench dowels visual alignment into wrench slot, some modifications to Gradel cassette sides are proposed (see Figure 44). [18]

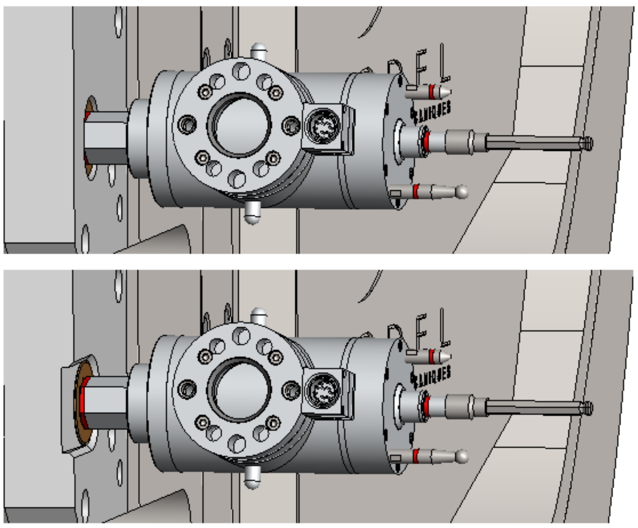

Figure 44: Insertion of WT [18]

Cassette side plate is original in the upper picture at Figure 44 and it has been modified in the lower picture. The red inspection groove is fully visible at the lower picture.

5.4 Testing of WPT

In this section development testing and qualification testing are performed for WPT.

5.4.1 Development testing

Development testing results for combined Wrench-Pin Tool, are gathered into Table 11.

Table 11: Development testing of WPT

Component	Testing reason	Testing against	Testing method	Result	Fault/ Remarks
Electric Motor of Pin Tool	Unproven technology	Function	Rotate	Pass	-
Optical Encoder	Unproven technology	Function	Read a measurement	Pass	-
Damping system of Pin Tool	Unproven technology	Function	Test sliding properties	Pass	-

Development testing results of WPT illustrates that all new components are functional for this design.

5.4.2 Qualification testing

Table 12 presents qualification testing results for WPT.

Table 12: Qualification testing results for WPT

Interface	Testing reason	Testing against	Testing method	Result	Fault/ Remarks
Manipulator – Tool body	New interface	Compatibility	Mock-Up	Pass	-
Tool body – U-support	New interface	Compatibility	Mock-Up	Pass	-
Pin tool – Pin slot	New interface	Compatibility	Mock-Up	Pass	-
Wrench tool – Wrench slot	New interface	Compatibility	Mock-Up	Pass	-

Qualification testing declares that all interfaces of WPT are compatible. RH compatibility shall be tested at later.

5.5 Verification of Cassette Locking process

Virtual verification, i.e. Task Description, for the Divertor Cassette Locking process can be made after the tools have been designed at preliminary stage. Visual verification is performed iteratively until designed tools successfully complete the locking process. Visual verification is performed in Delmia program and it is attached altogether in Appendix 2. Following attentions and actions arose during Task Description:

- WHJ interface plate shall be shorten to increase clearances (Figure 45)
- Length of WPT body´s lower dowel pins shall be minimized to increase clearance between WPT and WHJ (Figure 46)

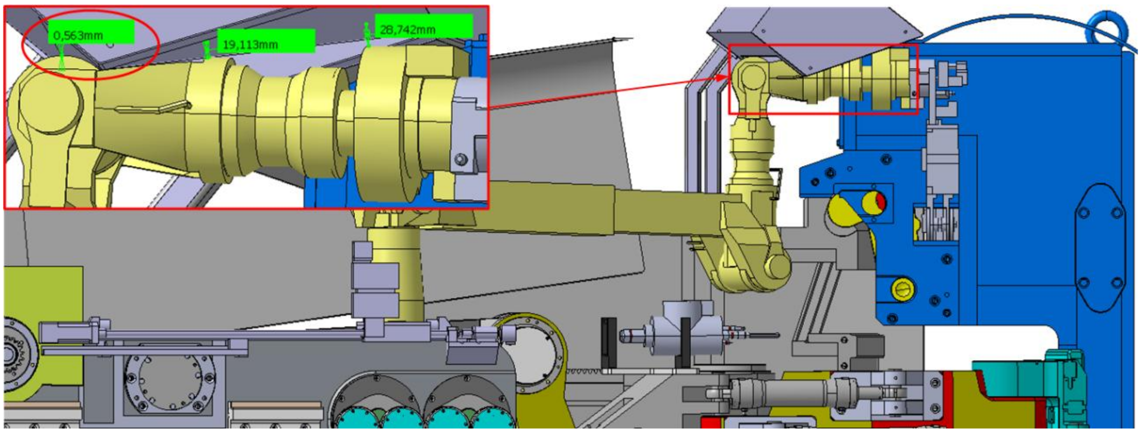

Figure 45: Small clearance (0.6 mm) between WHMAN arm and DRM at WHJ operation

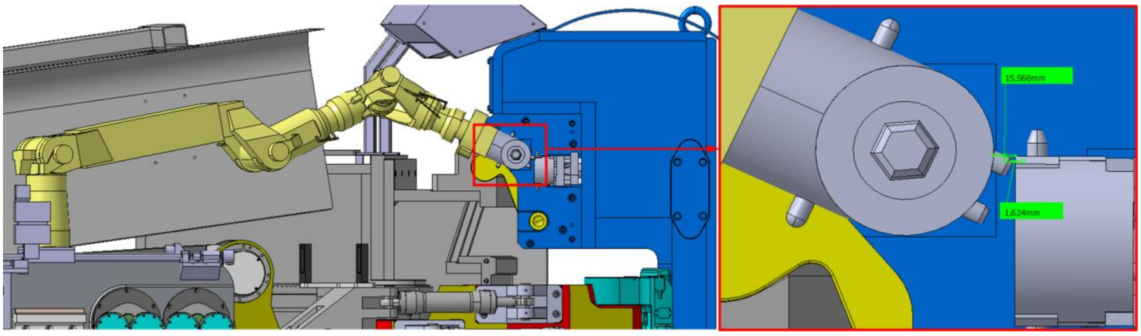

Figure 46: Small clearance (1.6 mm) between WPT and WHJ at WPT operation

6 Integration and Evaluation of CLS tools

This chapter presents the Integration and Evaluation phase for development CLS tools. First system is integrated and after that system development tests are performed and requirements are verified. The last section presents the evaluation process for the system developed but it is not possible to realize due to time limits of this thesis. However it can be applied for the forthcoming ITER Divertor cassette RH tool prototypes development processes.

6.1 System Integration

This section presents only the WHJ integration phase because it has more versatile subsystems than WPT. The WHJ integration begins from cleaning of all its hydraulic components. This is necessary, because WHJ has many new hydraulic components or parts and all of them shall be as clean as possible for high pressure water which is circulating in WHMAN and WHJ. Cleaning prevents for example stuck of WHMAN servo valves, breaks of sealing and scratches between sliding elements like cylinders. Components are assembled into subsystems after careful cleaning. After that subsystems are tested individually to ensure their desired behaviour. Leakage tests for components were performed at previous chapter and in this phase subsystems leakage shall be studied before subsystems are assembled together. Four On/Off valves, that have smallest internal leakage, are chosen for Control Block (#3 at Figure 28). WHJ hydraulic system tests are performed after all WHJ´s subsystems are tested individually and assembled together. Test configuration for assembled WHJ is presented in Figure 47.

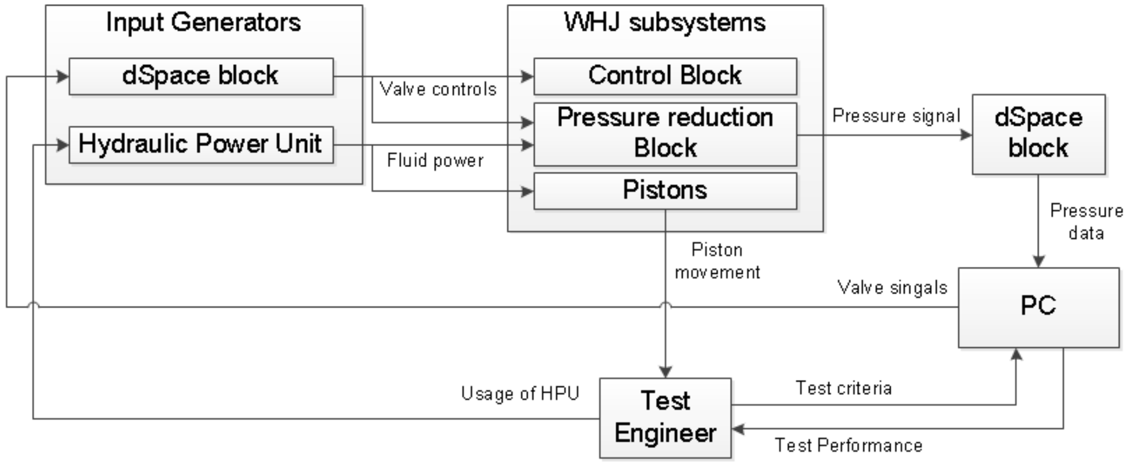

Figure 47: Test configuration for assembled WHJ

Analogy between this test configuration and subsystem test configuration presented in the theory (Figure 20) is that dSpace block has functions for *Input Generator* and *Output Analyzer*, PC including its software works as *Performance Comparator*. *Element Model* and *Test Control Unit* are excluded from the WHJ test configuration. The function of WHJ subsystems was verified by means of this test.

6.2 Developmental CLS System Testing

System testing objective is to verify the requirements that are developed at the beginning of the process. These requirements can be considered as system technical specifications. Development system testing is performed at Test Stand (TS) which is part of the DTP2 facility. Test Stand consists of real size Toolrack with U-supports, CLS Mock-Up and WHMAN equipped with the CLS tools which are under development. Test Stand environment is built for easy human access which enables quick repair and improving actions for the tools. Each requirement is tested individually remotely by WHMAN. The results of developmental testing for CLS tools are gathered in Table 13, Table 14 and Table 15.

Table 13: Developmental testing results for WHJ

Req. Id.	Requirement description	Verification level	Test method	Results/ Remarks
RHD-WHJ1	Information of WHJ passive joint angle shall be provided to the operator	Subsystem	Angle information from manually turned WHJ to the operator	Pass
RHD-WHJ2	Indication of the WHJ correct mounting depth to WHJ slot shall be provided to the operator	Subsystem	WHMAN insert WHJ remotely into its slot at TS	Not tested
RHD-WHJ3	WHJ hydraulic cylinders shall be operated remotely	Subsystem	Valves operated remotely by operator	Pass
RHD-WHJ4	WHJ shall withstand the load affected by compression of cassette without connection to manipulator	System	WHJ compress the SC at the DRM, after compression WHMAN is disengaged	Not tested
RHD-WHJ5	Hydraulic quick connectors shall be attached without pressure	Subsystem	Inspection of WHJ working pressure when supply line is closed (component 1.1 @ Figure 28) remotely by operator	Fail
RHD-WHJ6	Working pressure of WHJ shall be controlled	Subsystem	Inspecting and adjusting of WHJ working pressure	Pass
RHD-WHJ7	Indication of pressure reduction shall be provided to the operator	Subsystem	Comparison between supply line pressure and WHJ working pressure remotely by operator	Pass
RHD-WHJ8	WHJ pistons shall be retracted to the folded position in case of a hydraulic or an electric failure	Subsystem	-	Impossible to execute
RHD-WHJ9	WHJ dimensions shall be such that collisions between WHMAN/WHJ and DRM are avoided	System	Turning of WHJ remotely in the DRM by operator	Not tested (virtual pass)

The major remark in the WHJ testing results is requirement RHD-WHJ5 which has been failed. Failure has been noticed at the output of WHJ pressure transducer (component 2.3 at Figure 28). The transducer shows that the pressure in WHJ rises slowly to same value with supply pressure. The pressure rising is caused by leakage in the WHMAN supply line. Flo Control On/Off valves have been installed at the supply line and the great variety of inner leakage has been noticed between different units at the earlier phase of the process. The unfulfilled requirement is traceable to the poor sealing capability of On/Off valve. The sealing capability can be improved by changing the valve´s sealing pairs. If this does not affect, the cavities of self-made hydraulic block need to be inspected and modified precisely with the original cavity of Flo Control valve.

The requirement RHD-WHJ2 has not yet been tested with the manipulator and it can’t be verified in the time limit of this thesis. The requirement RHD-WHJ8 is impossible to execute with the current dimensions of the WHJ because it need spring returning pistons. Requirements RHD-WHJ4 and RHD-WHJ9 cannot be tested at the Test Stand because the interactions of Divertor Cassette and the Maintenance tunnel are impossible execute at the Test Stand. These two requirements should be fulfilled at the later phase of the process in operational test phase.

Table 14: Developmental testing results for the Wrench Tool

Req. Id.	Requirement description	Verification level	Test method	Results/ Remarks
RHD-WT1	Indication of the correct mounting depth shall be provided to operator	Subsystem	Insertion inspected from camera view	Pass
RHD-WT2	Wrench tool shall provide means for reliable alignment into wrench slot double hex socket.	Subsystem	WHMAN insert WT remotely into its slot at TS by operator	Pass

Table 14 illustrates that the RH requirements of Wrench Tool are completely verified. From the results can be concluded that the Wrench Tool is ready for operational tests.

Table 15: Developmental testing results for the Pin Tool

Req. Id.	Requirement description	Verification level	Test method	Results/ Remarks
RHD-PT1	Locking screw’s ends of motion shall be detected and jamming avoided.	Subsystem	Motion inspected remotely by operator	Pass
RHD-PT2	Pin tool Allen key shall reach at SC locking screw’s hex socket.	Subsystem	WHMAN insert PT into its slot remotely at TS by operator	Pass
RHD-PT3	Pin tool shall provide means for Allen key’s reliable alignment into SC locking screw hex socket.	Subsystem	WHMAN insert PT into its slot remotely at TS by operator	Pass
RHD-PT4	Current position of locking pins shall be measurable.	Subsystem	Motion inspected remotely by operator	Pass
RHD-PT5	Measured value of locking pins position shall be absolute value for case of power failures.	Subsystem	Software makes a point of position reference and it is checked against pin movement	Pass
RHD-PT6	In case of SC locking mechanism jamming, there shall be back-up system to open the jam.	Subsystem	-	Not executed

Results of the Pin Tool developmental testing demonstrate that all but one of its technical specifications are fulfilled. RH Safety requirement (RHD-PT6) has not been made in this process, but there is one free U-support for the high torque tool for emergency cases. Pin Tool is ready for operational testing despite of this one requirement.

6.3 Acceptance testing

Acceptance tests are not possible to carry out in the time limits of this Thesis due to fact that Second Cassette side plate requires certain modifications for RH operations and it cannot be machined in these limits. The idea of the testing is illustrated here, because it can be applied for the forthcoming ITER Divertor cassette tooling development processes.

Acceptance testing i.e. operational tests may begin after all feasible technical specifications of WHJ are verified at the Test Stand because testing on this level concentrates only on operational requirements. Acceptance testing of developed CLS tools occurs at the Divertor Region Mock-Up instead of the Test Stand. All necessary systems for the Cassette locking (illustrated in Figure 11) process must be installed into the DRM. The objective of the testing is to validate the system developed by testing these operational requirements of the tools:

- ***WHJ:*** Water Hydraulic Jack shall provide the mechanism to compress the SC.
- ***WT:*** Wrench Tool shall provide the driving mechanism to operate CLS latches.
- ***PT:*** Pin Tool shall provide the driving mechanism to operate SC locking mechanism to lock and unlock SC latches.

These requirements are verified by performing the full Second Cassette Locking procedure (specific RH tasks are described in Appendix 2) via Remote Handling operations. The real Cassette's interaction can be tested first time in these testing. The Cassette affects differently to each tool: for WHJ it generates real loading situation for pistons (affected by Cassette spring constant and sliding), for WT it generates real loading situation for WHMAN joints (affected by mass and friction of the latch) and for PT it generates real torque for its electric motor (affected by mass and tolerances of pins).

7 Conclusions

In the Thesis, Engineering Development phase of Systems Engineering was studied and applied for the RH tools. Requirements Development methods were utilized for the RH specific requirements during the development process. Divertor Cassette Locking tools were designed according to the RH specific requirements and each new designs, components and interfaces were tested individually. After the design process, the RH tools were integrated and tested against the RH specific requirements as an operating whole. The manufactured tool prototypes are presented in Figure 48. The acceptance testing for the CLS tools was not performed, but the idea was presented.

The overall testing results express that majority (65 %) of RH requirements were fulfilled. 29 % of requirements are not yet tested (or impossible to execute with current design) and they may be fulfilled easily. One requirement was failed but the repair actions have been planned for this failure.

The development method which is utilized in the Thesis for the RH Tools may be utilized as a guideline for forthcoming development process of new generation Divertor Cassette locking Tools.

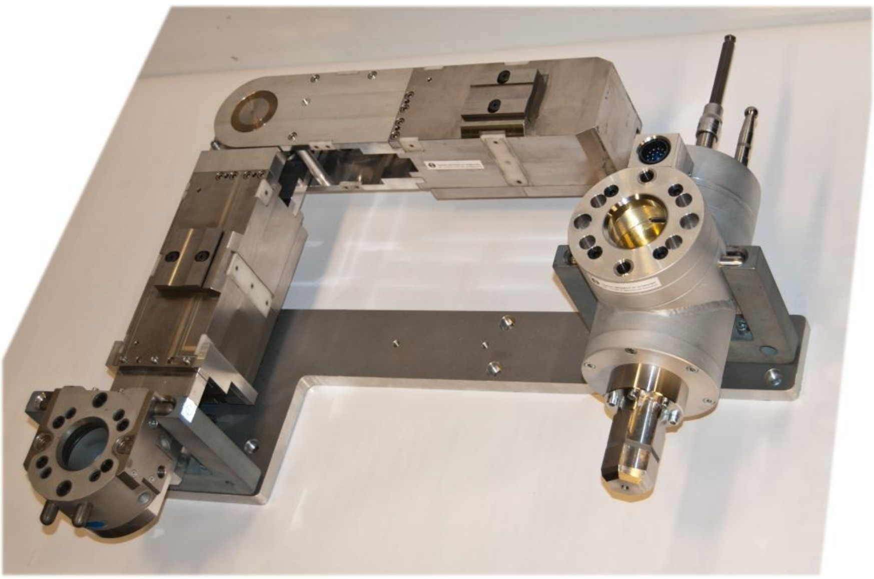

Figure 48: Manufactured Tool prototypes

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Appendix 1: Finite Element Analysis for the contact between WHJ Pushing Plates and SC Latches

Finite Element Analysis (FEA) for the new design of pushing plates is presented in this appendix presents. Earlier FEM analyses shows that Von Mises stress is around 300 MPa in the pushing part and contact pressure is less than 400 MPa at the contact when the contact transmits 500 kN load. [8] New FEM analyses have been made with 280 kN (140 kN for each contact) load for the current design and a new design. Following figures illustrates new FEM analyses at the contact (from Figure 49 to Figure 51 left figure is for current design and right figure for new design). Typical yield strength (Rp 0.2) and tensile strength (Rm) of the contact materials are represented in Table 16.

Table 16: Contact material properties [8]

Pushing part		
Material	**Rp 0.2 [MPa]**	**Rm [MPa]**
Stainless Steel EN 1.4418	730	930
SC latches		
Material	**Rp 0.2 [MPa]**	**Rm [MPa]**
Aluminum bronze	399	671

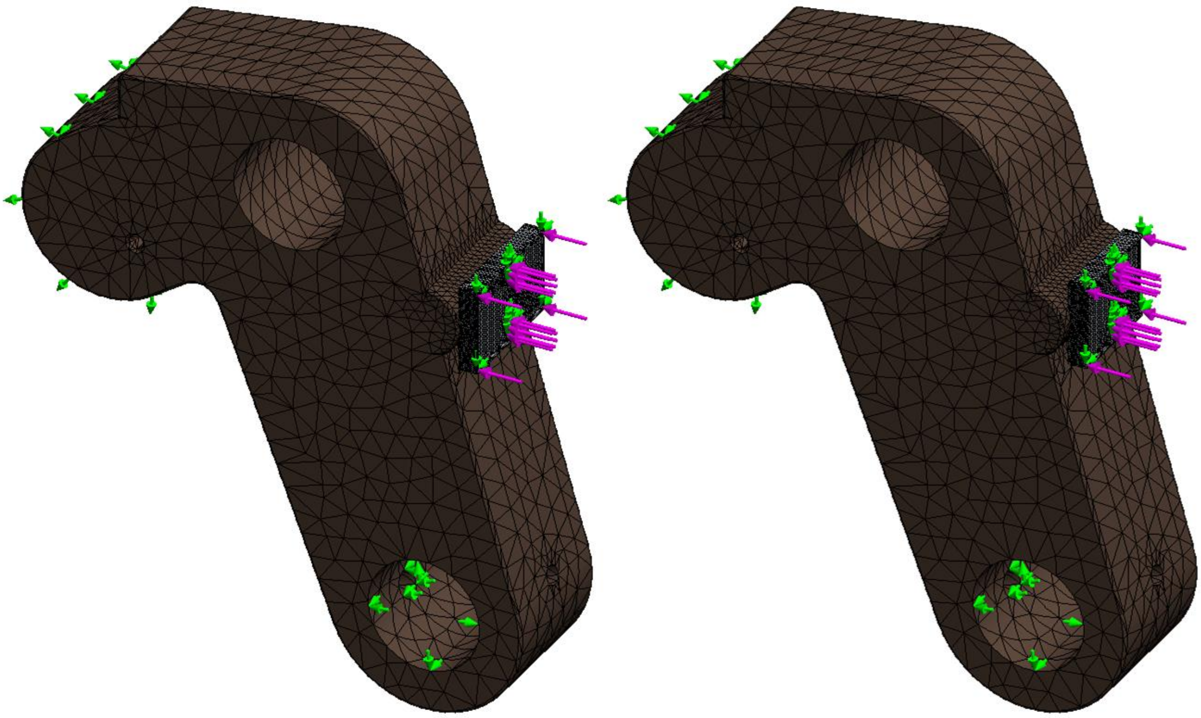


Figure 49: FEM mesh and loading conditions

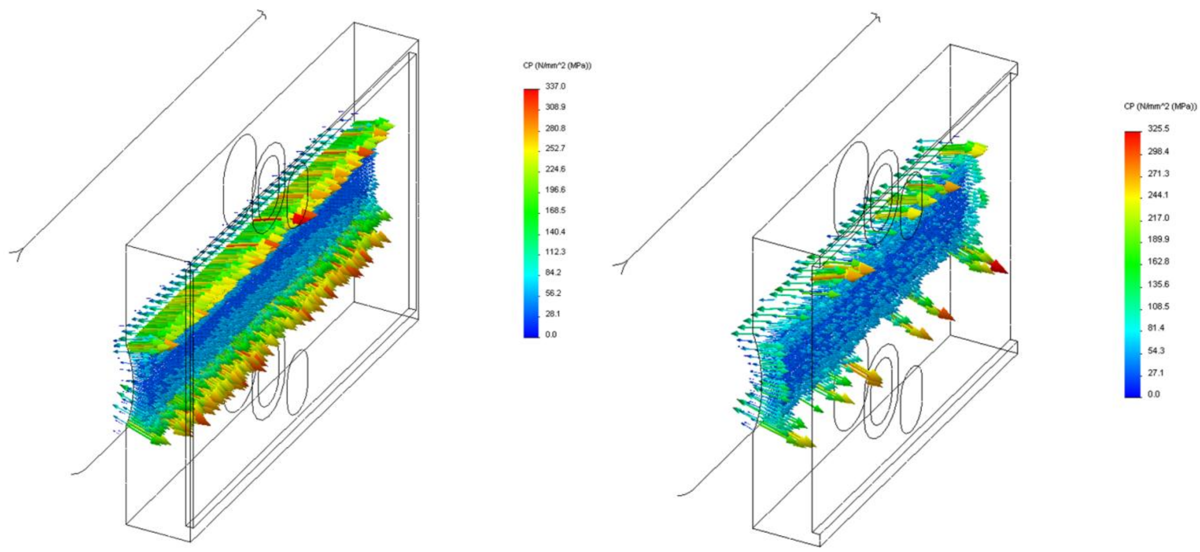


Figure 50: Contact pressure at the contact

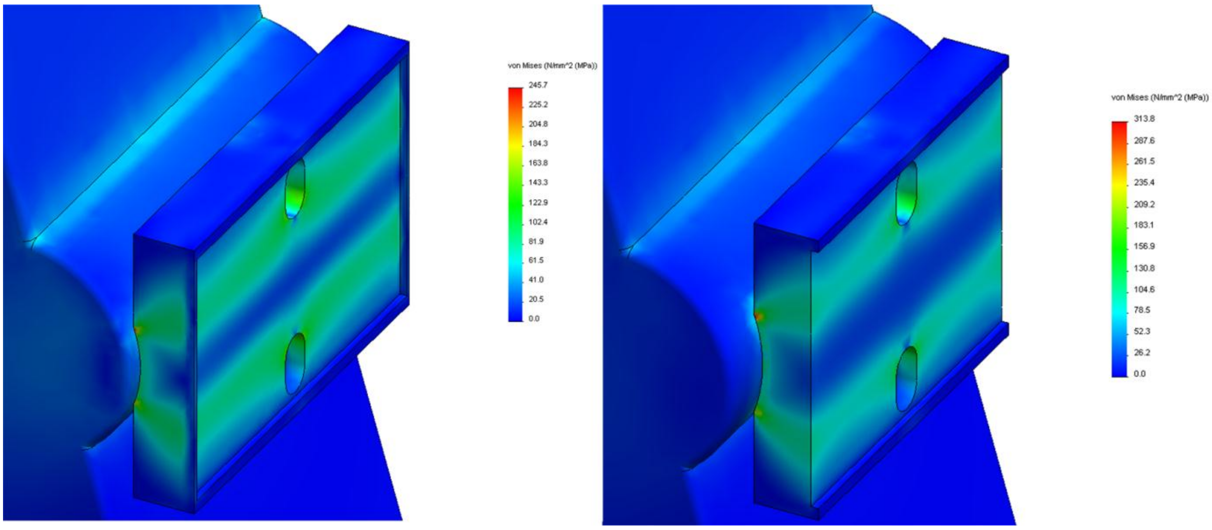


Figure 51: Von Mises stress in the contact parts

FEM analyses shows that the new design is feasible for new lower loading conditions. The contact pressure and Von Mises stress are more uniformly distributed in the new design than the current design. The average contact pressure is higher and the peaks are lower in the new design. Results of FEM analyses are shown in Table 17. The FEM studies shows that in the new design average Von Mises stress is below 200 MPa and the contact pressure is around 100 MPa if the peaks are not taken count. The earlier tests have proved that some yielding may occur at the surfaces of pushing plates and SC latches. [8] The yielding situates near at the edge of the contact due to profile of contact pressure.

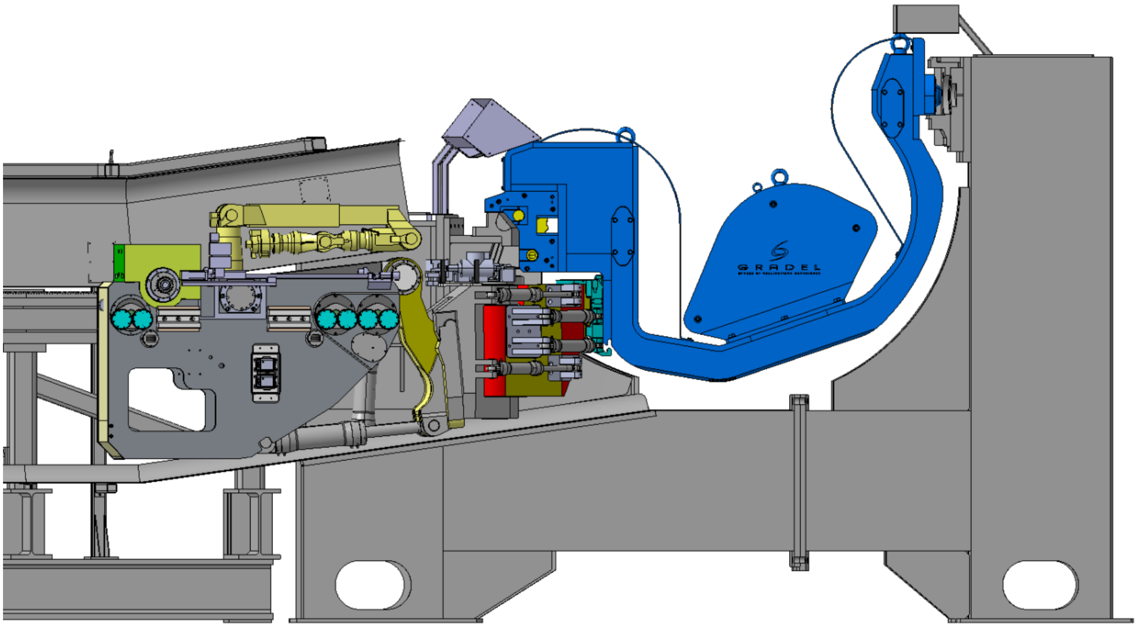
Table 17: Results of FEM analyses

Parameter	Current Design	New Design	Unit
Max. Contact Pressure at the contact	337	325,5	MPa
Max. von Mises Stress in Latch	81	97	MPa
Min. Factor of Safety at Latch for yielding	4,92	4,11	-
Max. von Mises Stress in Pushing part	245,7	313,8	MPa
Min. Factor of Safety at pushing part for yielding	2,97	2,33	-

Appendix 2: Updated RH Task Description for WHMAN in SC Locking procedure

In this appendix, an updated RH TD with conceptual WHMAN tool mock-ups, developed in previous chapters, will be represented.

Task Description	Locking of the Second Cassette in the DRM
Task Objective	
• To move CMM/SCEE joints to the zero position • To unfold WHMAN with the unfolded position of the CMM • To connect the wrench tool to WHMAN • To rotate the latches of the Second Cassette • To connect WHJ to WHMAN • To compress the latches of the Second Cassette • To connect the pin tool to WHMAN • To lock the latches of the Second Cassette	
Target Plant	
• Second Cassette	
Start Point	
• SCEE is supported by CMM in cantilever manner • SC is disengaged from SCEE and is resting on the DRM • WHMAN is folded	
End Point	
• SC is locked inside the DRM • WHMAN is folded	
Assumptions	
• The elastic deformation of SC and remote handling equipment – induced by gravitational loads - has been neglected during the analysis of the boundary conditions in the assembly process.	
Main Issues	
• The bending of the Second Cassette (together with CMM/SCEE) is not considered during the transportation. Structural flexibility may cause changes to the SC installation sequence.	

Remote Handling Sequence
1. Start Point • SC is disengaged from CMM/SCEE and is resting on the DRM. • WHMAN is folded.  **Figure 52:** Starting Position in the DRM

2. CMM/SCEE joints moved to zero position

- CMM/SCEE is aligned with the DRM duct as depicted in the figure below.
- CMM/SCEE is lowered down to increase the available space for using tools and for unfolding of WHMAN.

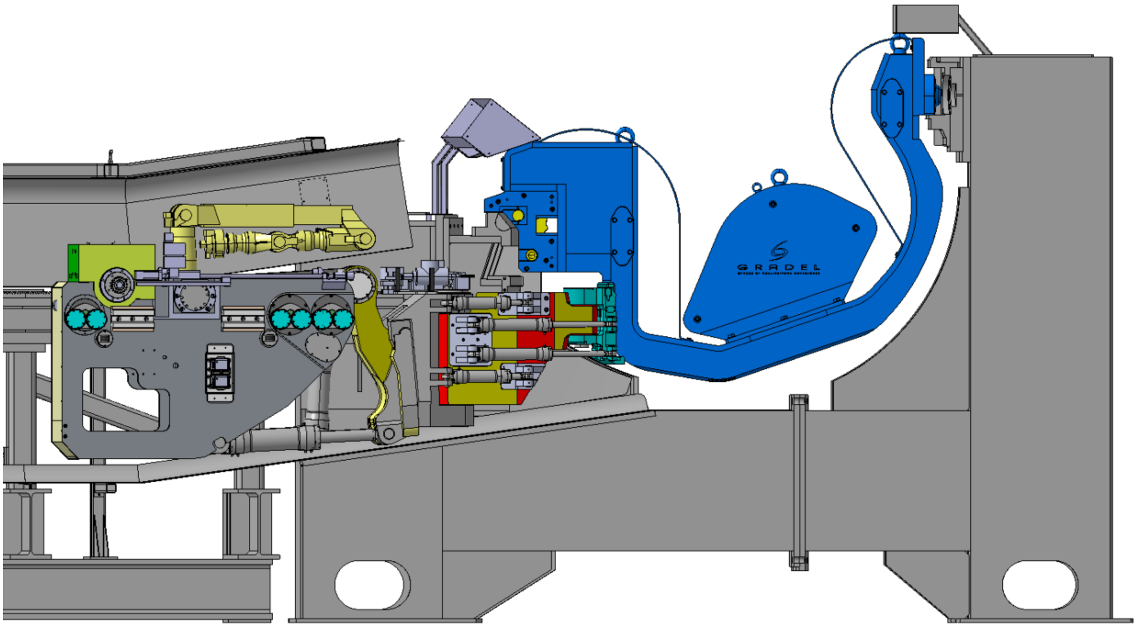


Figure 53: CMM/SCEE moved to zero position

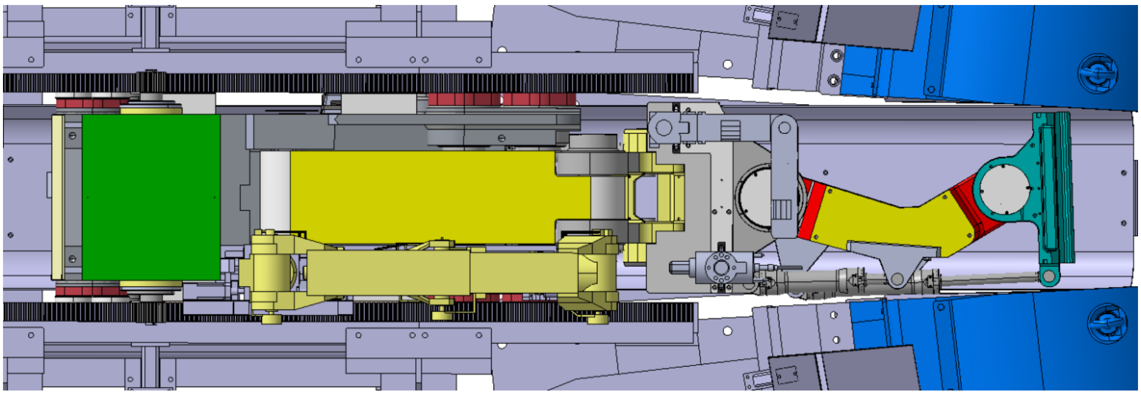


Figure 54: CMM/SCEE moved to zero position

3. Unfolding WHMAN

Unfolding WHMAN can be split in three different stages :

3.1 WHMAN preparation
3.2 Unfolding WHMAN´s elbow
3.3 Unfolding WHMAN´s wrist

3.1 WHMAN preparation

- Sliding table moves forward.
- WHMAN´s elbow reaches a high position to not collide with tools.

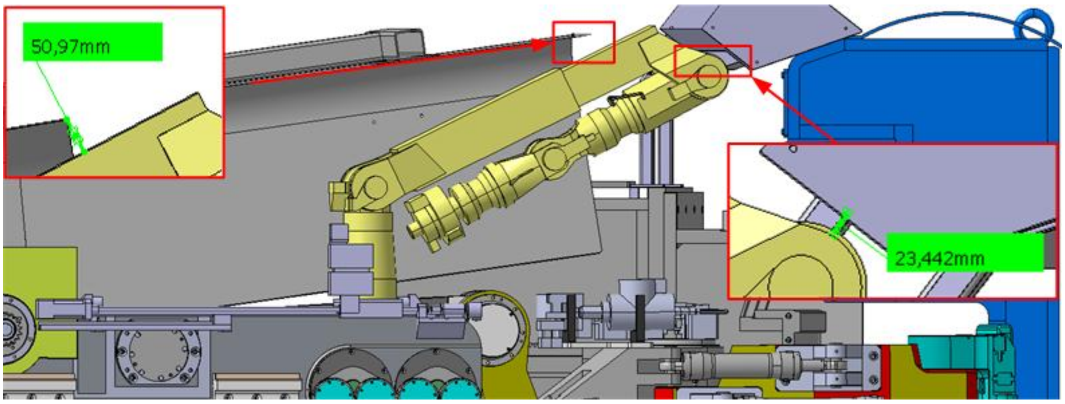


Figure 55: WHMAN preparation to unfold

3.2 Unfolding WHMAN´s elbow

- This movement is more critical and the clearances are much more reduced.
- This position directly limits the available space for tools on the toolrack.

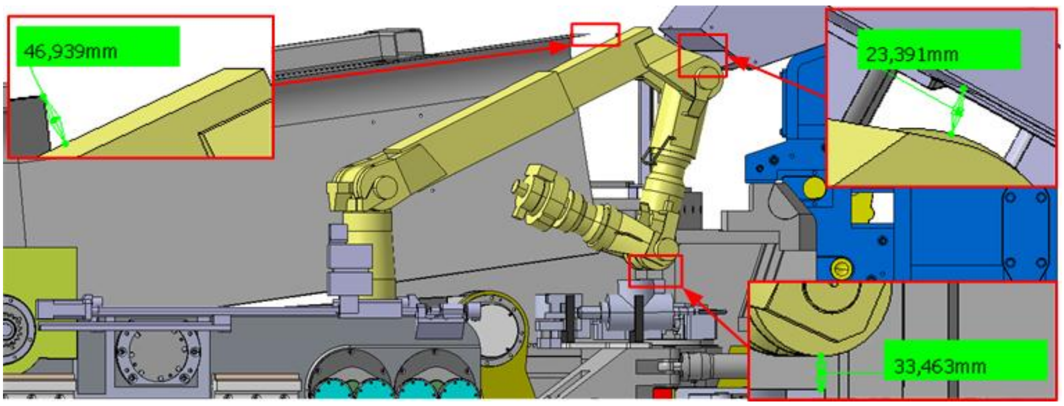


Figure 56: Unfolding WHMAN´s elbow

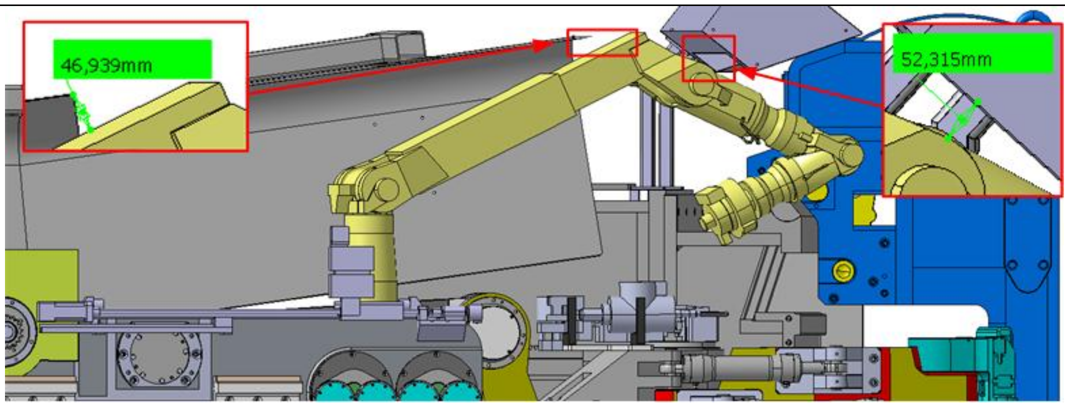


Figure 57: WHMAN´s elbow unfolded

3.3 Unfolding WHMAN´s wrist

- Once the highest tools avoided, the clearance with the upper part of the DRM can be increased.

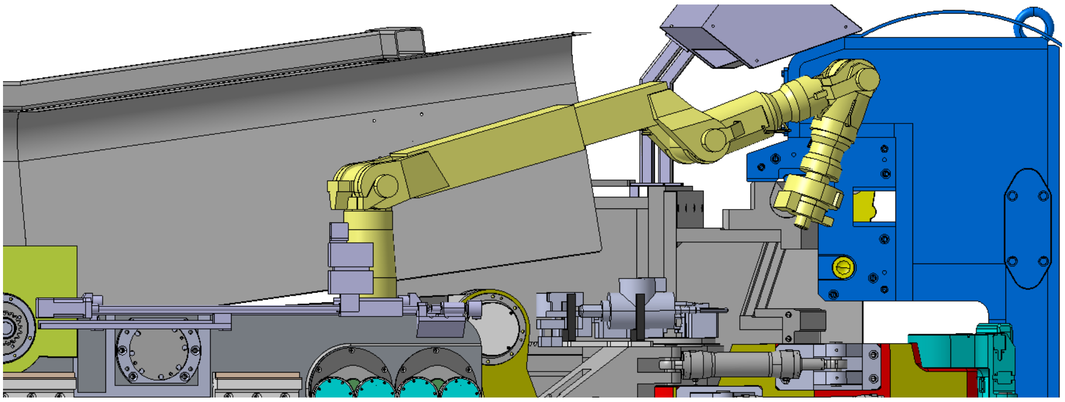


Figure 58: Unfolding WHMAN´s wrist

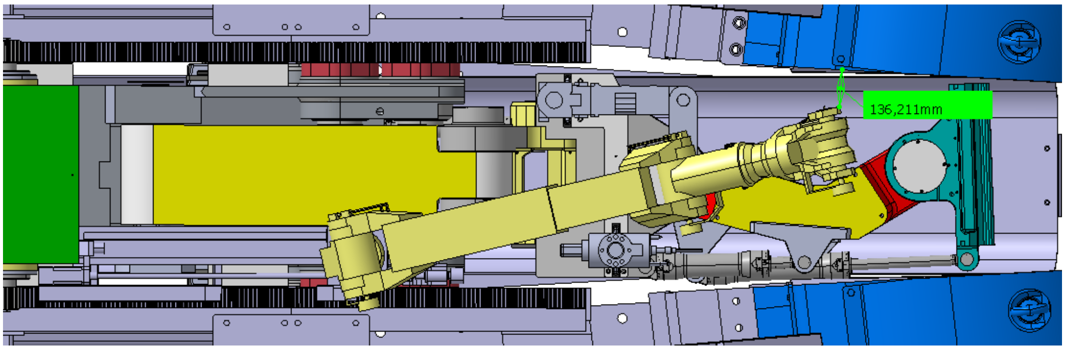


Figure 59: Unfolding WHMAN´s wrist

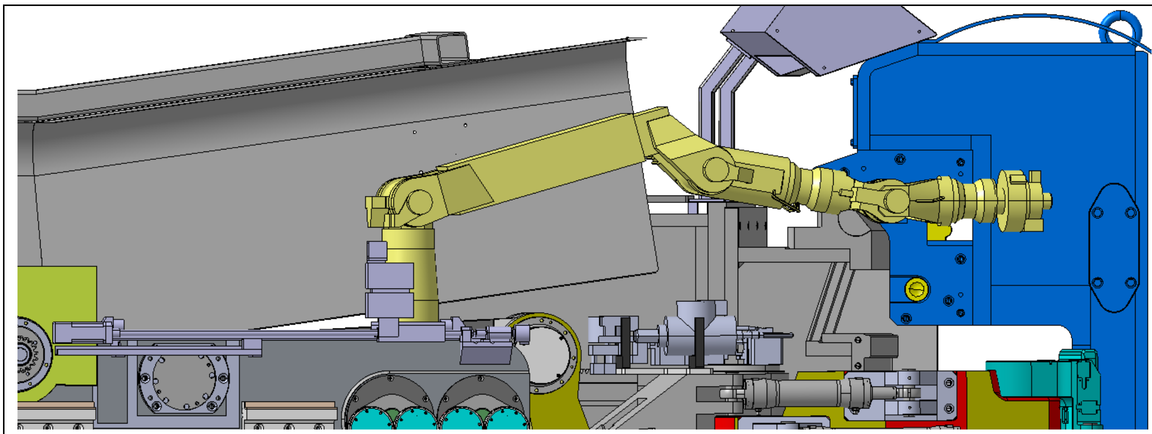


Figure 60: WHMAN´s wrist unfolded

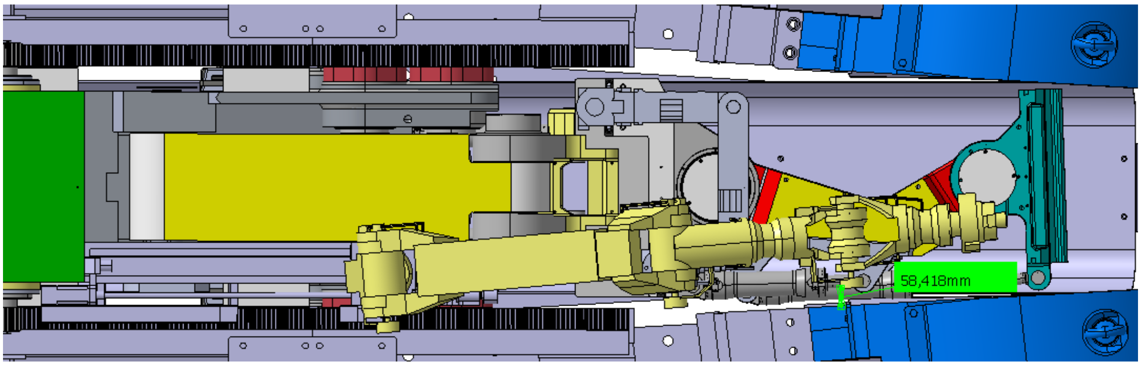


Figure 61: WHMAN´s wrist unfolded

4. Cassette latches rotating

Cassette latches rotating can be split in five different stages:

4.1 Connect WHMAN to the wrench tool
4.2 Reach the wrench tool to the wrench slot
4.3 Insert the wrench tool in the wrench slot
4.4 Rotate the latches
4.5 Place the wrench tool back on the toolrack

4.1 Connect WHMAN to the wrench tool

- WHMAN joints are continuously adjusted in order to insert the wrist into the wrench tool with a linear trajectory.

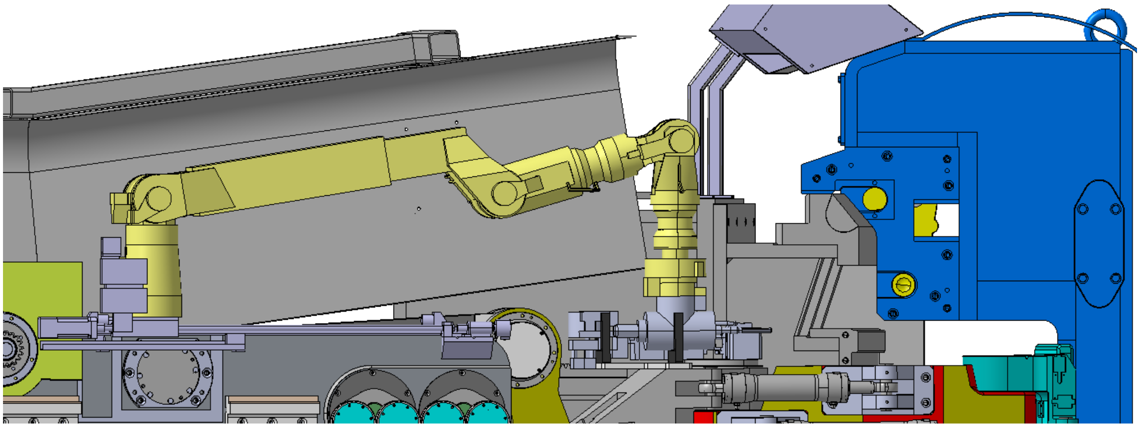


Figure 62: Connecting WHMAN to the wrench tool

4.2 Reach the wrench tool to the wrench slot

- WHMAN joints are continuously adjusted in order to lift the wrench tool off from the U-support of toolrack with a linear trajectory.

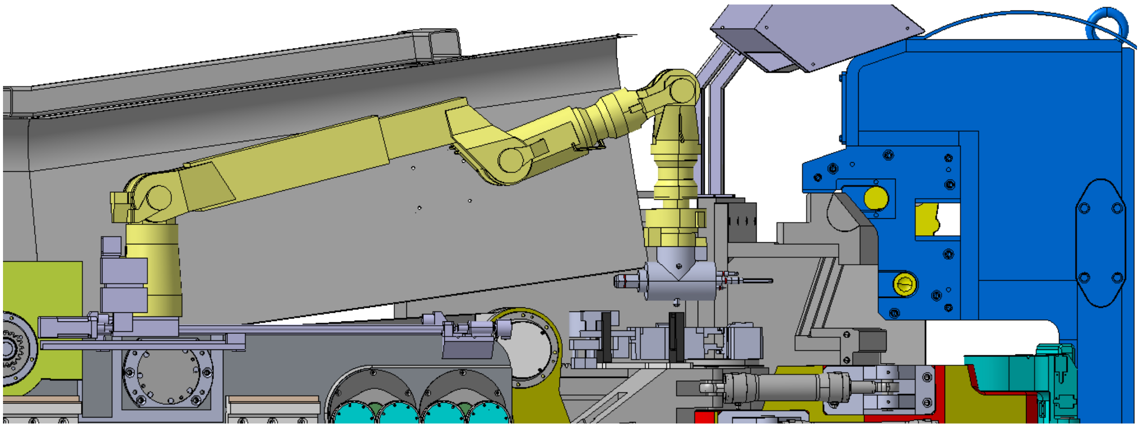


Figure 63: Lifting the wrench tool from U-support

- Sliding table moves forward to the working position of the wrench tool
- WHMAN joints are continuously adjusted in order to align the wrench tool co-incident with the double hex nut at the end of latch shaft (wrench slot).

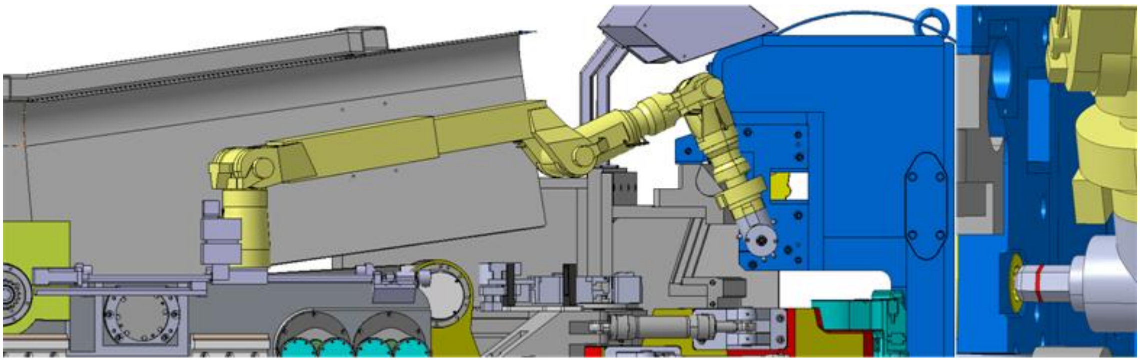


Figure 64: Alignment of the wrench tool and illustrated camera view

4.3 Insert the wrench tool in the wrench slot

- WHMAN joints are continuously adjusted in order to insert the wrench tool with a linear trajectory parallel to the latch shaft until the red groove is disappeared into the double hex nut (visual verification with camera).

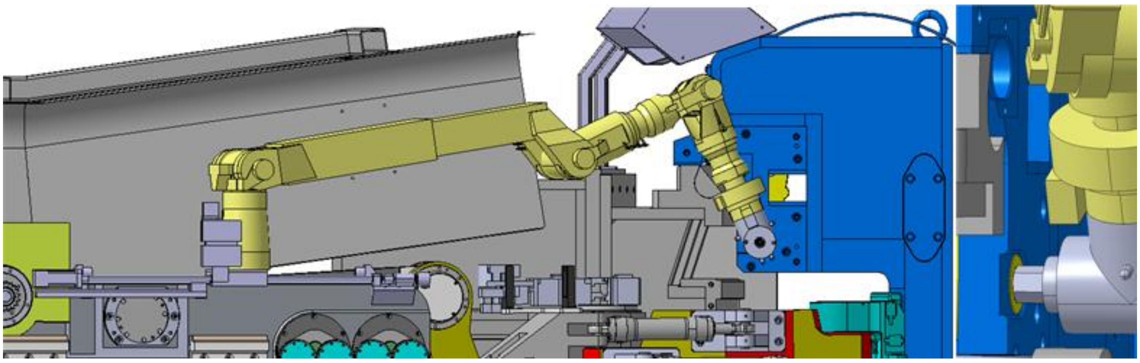


Figure 65: Inserting the wrench tool to wrench slot and illustrated camera view

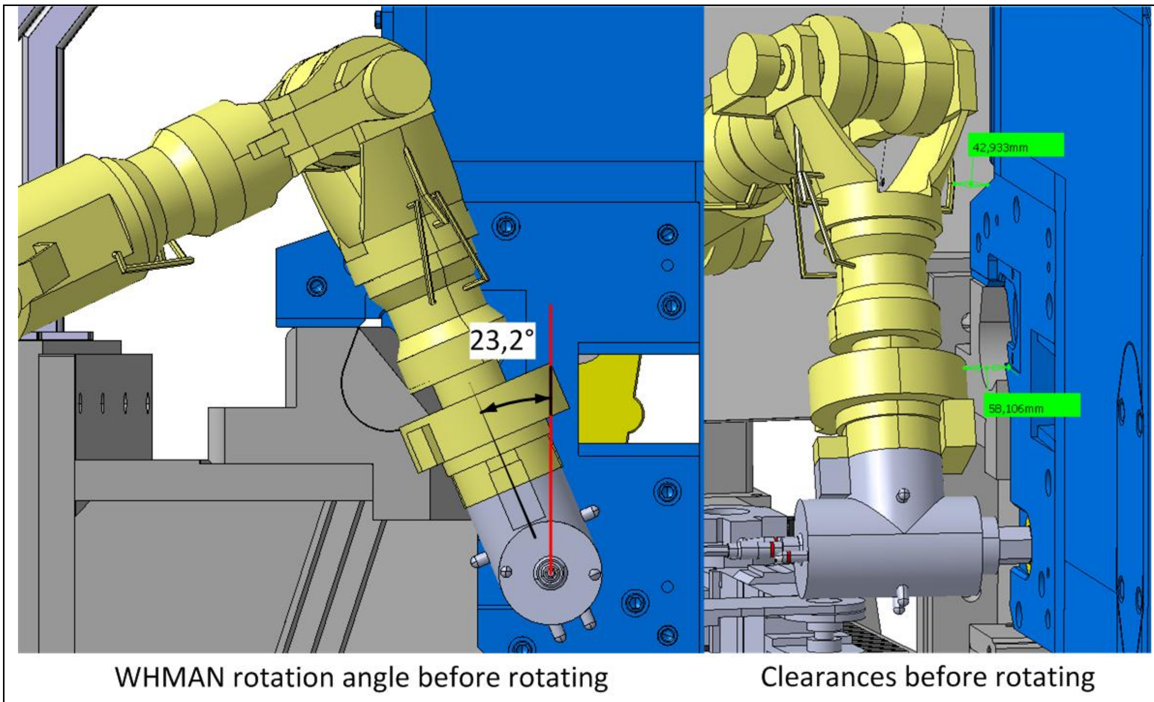


Figure 66: Latch rotation angle and clearances before rotating

4.4 Rotate the latches

- The WHMAN turns the wrench tool which turns the latches of the SC until they are in a contact with the DRM counterparts (approximately 15.7°).

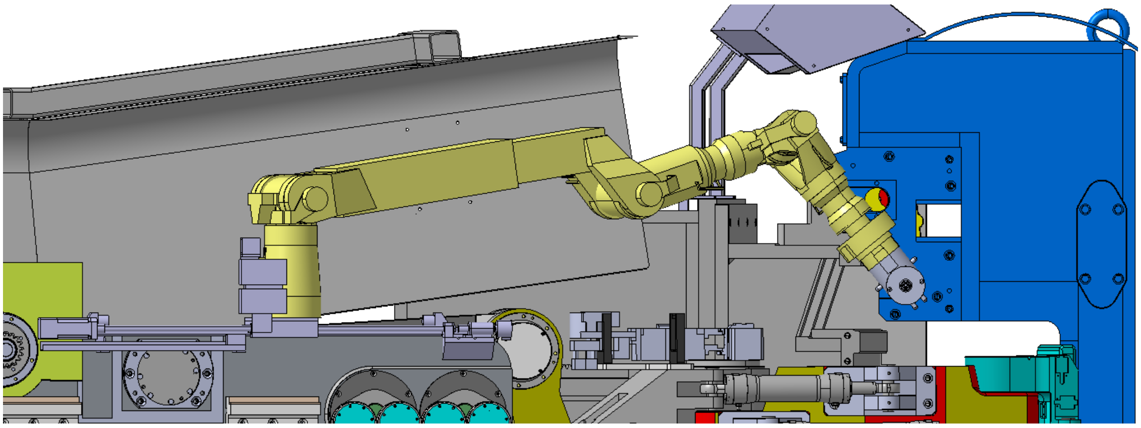
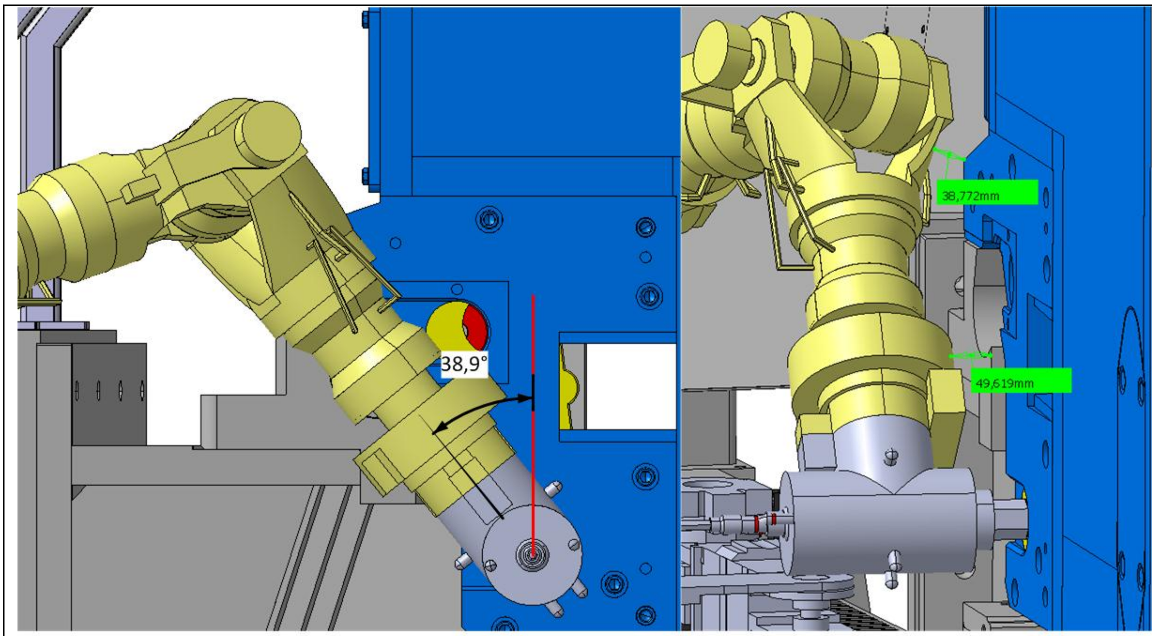


Figure 67: Rotating the latch



WHMAN rotation angle after rotating   Clearances after rotating

Figure 68: Latch rotation angle and clearances after rotating

4.5 Place the wrench tool back on the toolrack

- Sliding table moves backward to the home position
- WHMAN joints are continuously adjusted in order to align the wrench tool co-incident with the U-support of toolrack.

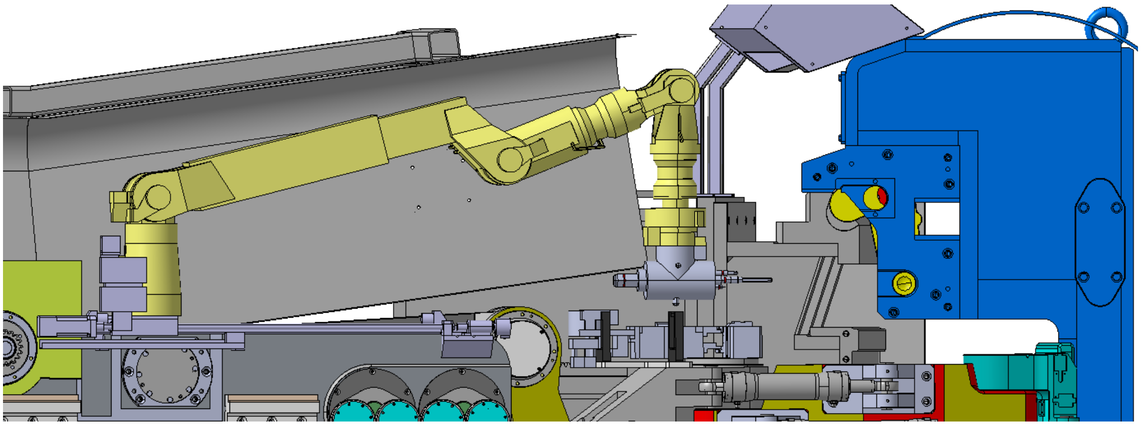


Figure 69: Lowering the wrench tool on the U-support

- WHMAN joints are continuously adjusted in order to lower the wrench tool back to the U-support of toolrack with a linear trajectory.

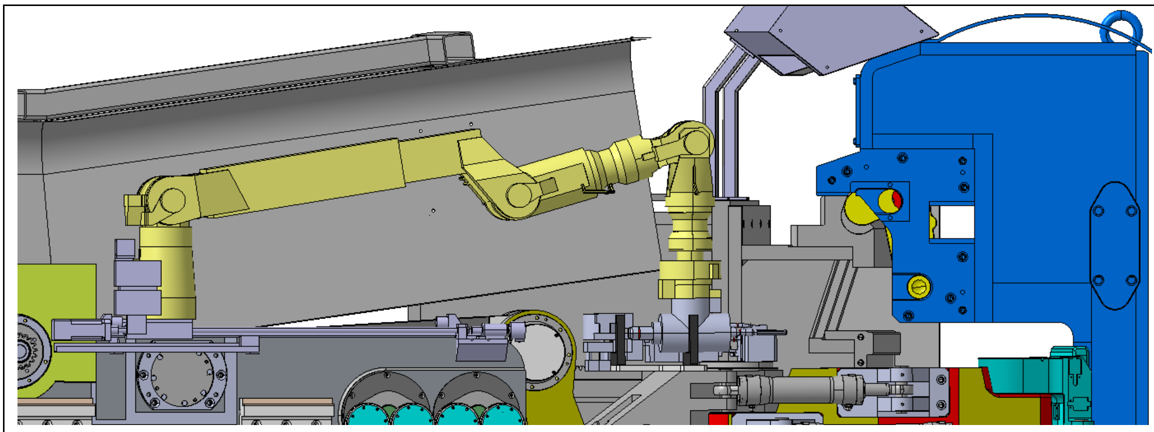


Figure 70: Releasing the wrench tool on the toolrack

5. Installation and pressurisation of the WHJ

The compression process of the SC can be split in four different stages:

5.1 Connect WHMAN to WHJ
5.2 Reach the cassette slot for WHJ
5.3 Unfold WHJ
5.4 Compress the SC

5.1 Connect WHMAN to WHJ

- WHMAN joints are continuously adjusted in order to insert the wrist into WHJ with a linear trajectory.

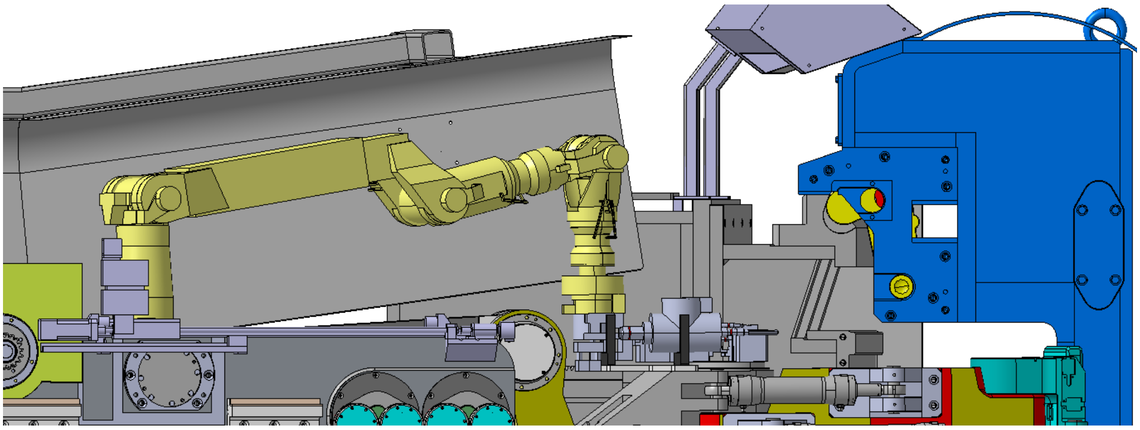


Figure 71: Connecting WHMAN to WHJ

5.2 Reach the cassette slot for WHJ

- WHMAN joints are continuously adjusted in order to lift WHJ off from the U-support of toolrack with linear trajectory

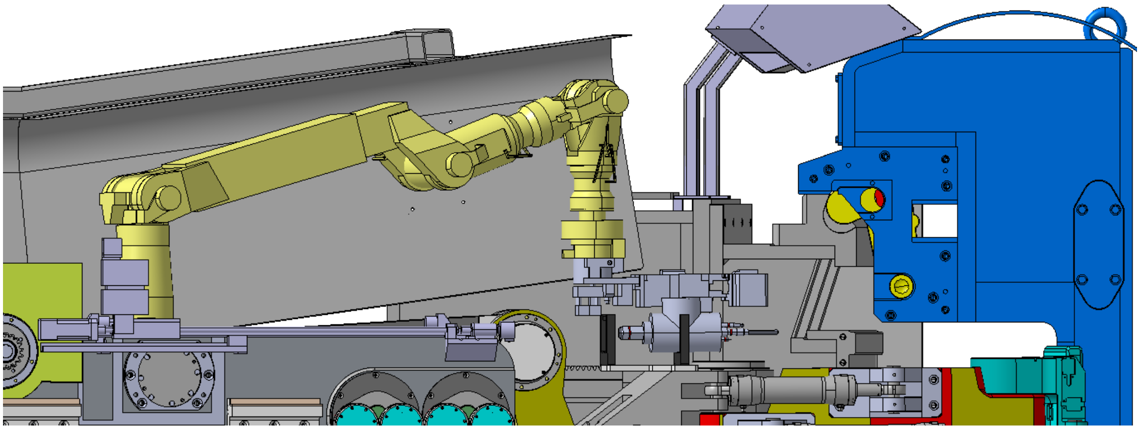


Figure 72: Lifting the WHJ from U-support

- Sliding table moves forward to the working position of WHJ
- WHMAN joints are continuously adjusted in order to reach the WHJ to cassette's slot.

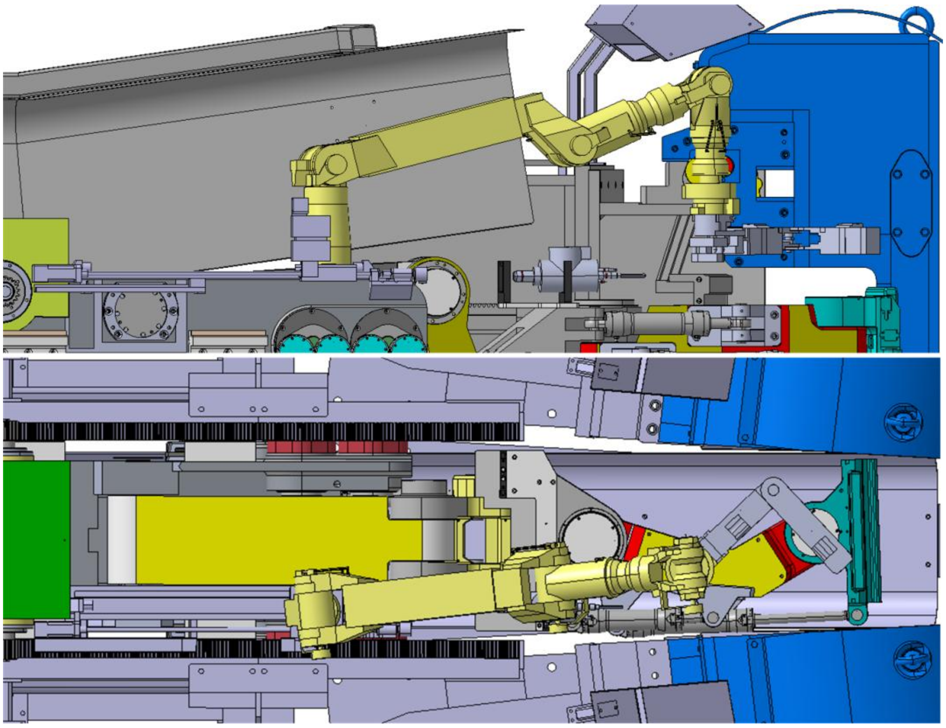


Figure 73: Turning the WHJ in the DRM

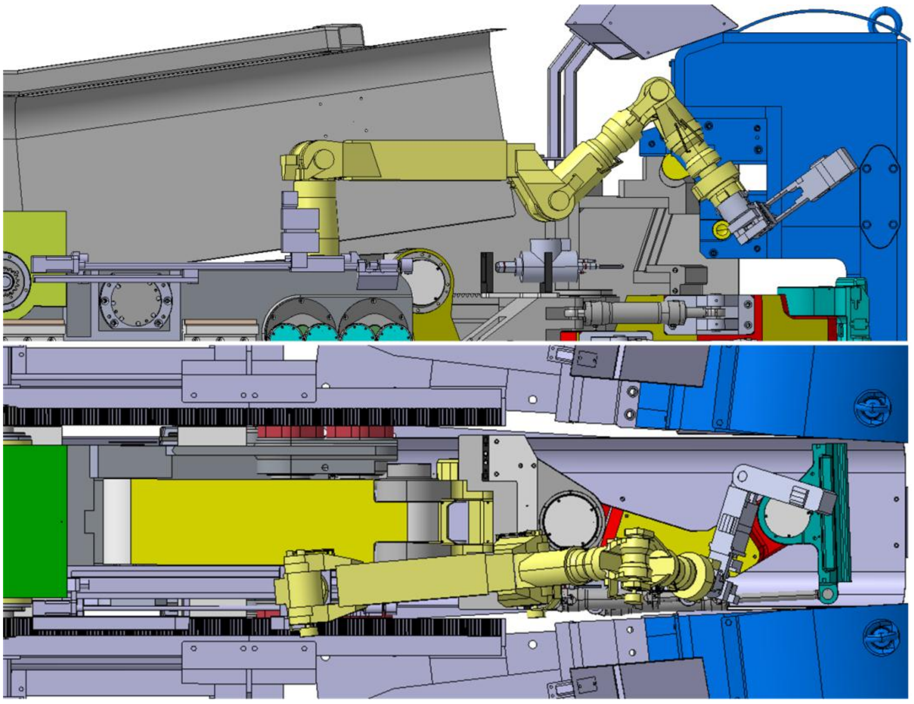


Figure 74: Turning the WHJ in the DRM

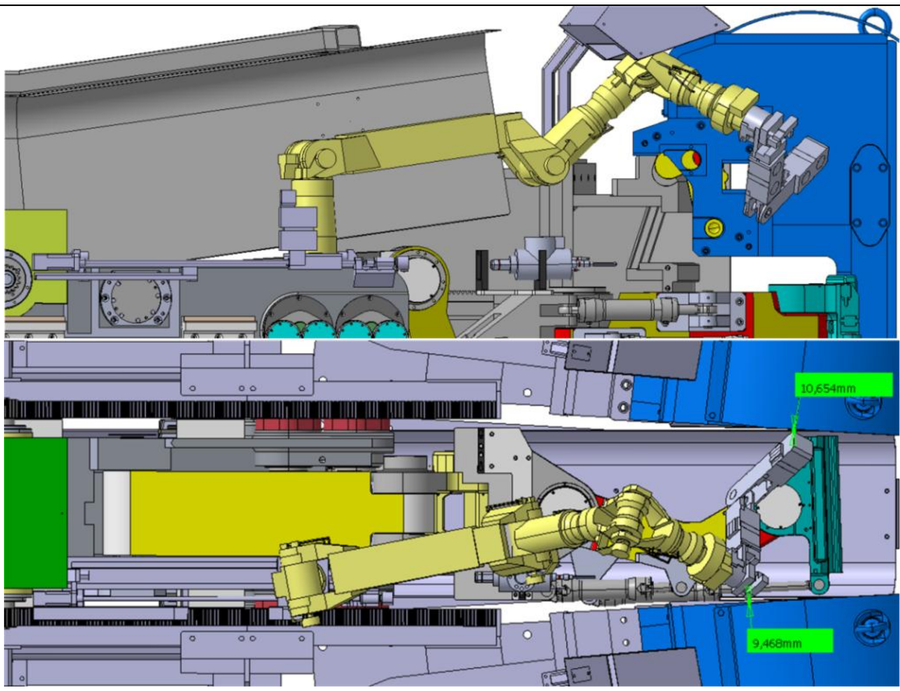


Figure 75: Turning the WHJ in the DRM

- WHMAN is set in a position that doesn´t collide with the upper part of the DRM.
- A clearance of 10.8 mm appears between WHMAN and the upper part body of the DRM with the current models using the joint limits of WHMAN.

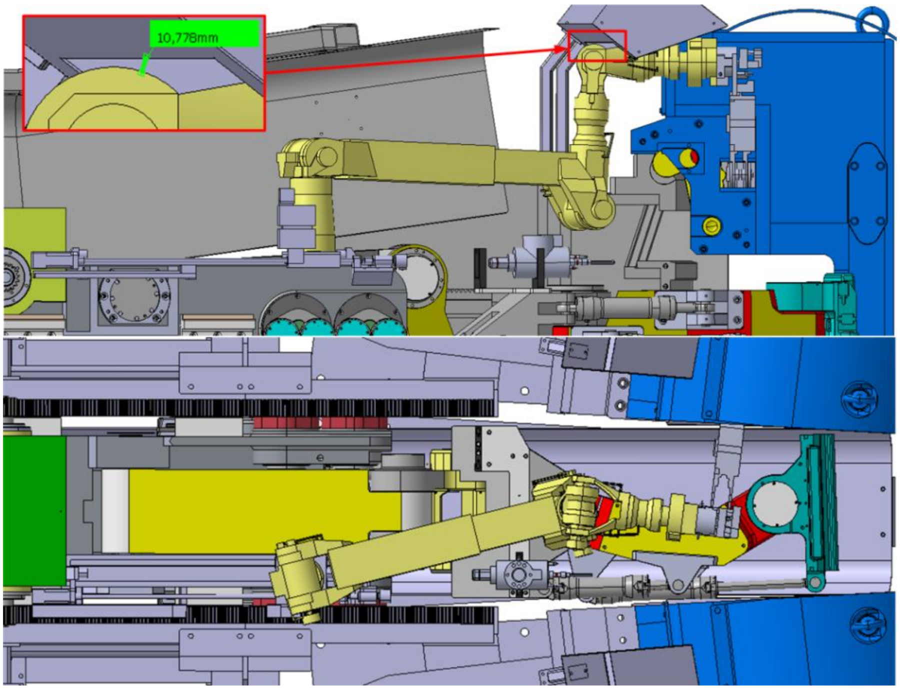


Figure 76: Turning the WHJ in the DRM

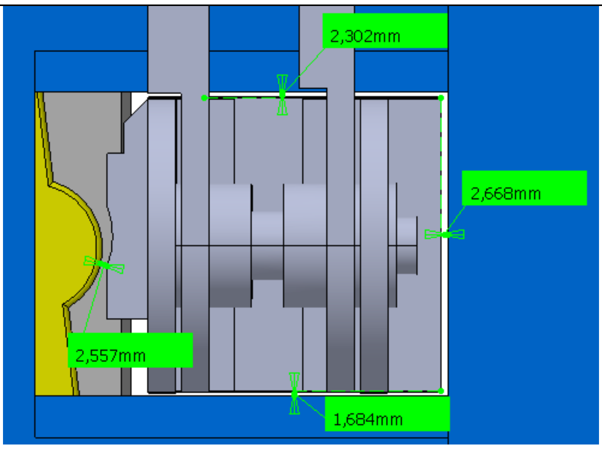


Figure 77: Clearances during the insertion of WHJ

- WHMAN joints are continuously adjusted in order to insert WHJ with a linear trajectory parallel to the cassette slot´s direction.
- The trajectory of the wrist is linear to avoid collision with the DRM.
- A clearance of 9,5 mm appears between WHMAN and the upper part body of the DRM with the current models using the joint limits of WHMAN.

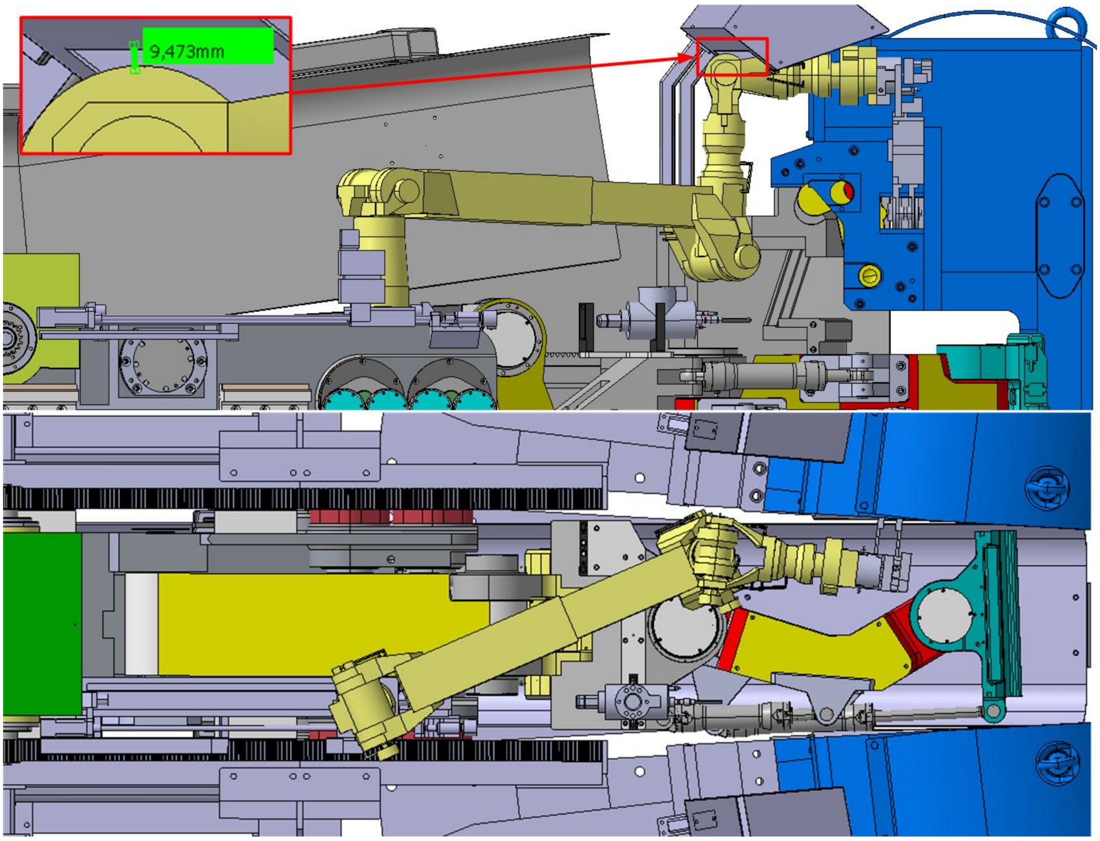


Figure 78: Inserting the WHJ into its slot

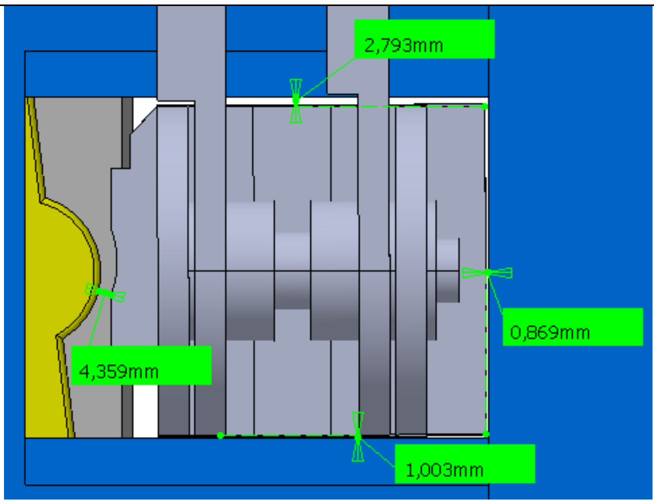


Figure 79: Clearance before unfolding of WHJ

5.3 Unfolding the WHJ

- WHMAN starts unfolding WHJ approximately 30° to increase the clearance between the wrist and the upper part of the DRM.
- The aim of this step is to let some available space for tools without colliding with the upper part of the DRM.

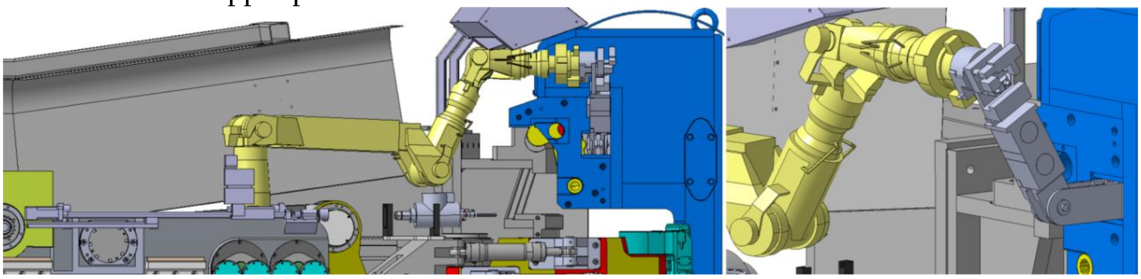


Figure 80: WHMAN starting to unfold WHJ

- The sliding table moves backward.
- WHMAN joints are continuously adjusted in order to keep WHJ at the same position.

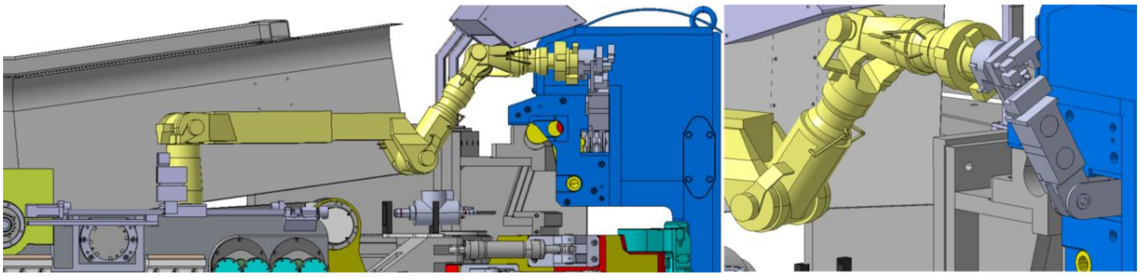


Figure 81: The sliding table moving backward

- WHMAN joints are continuously adjusted in order to unfold WHJ with a circular trajectory.
- Angle of passive joints of WHJ turns approximately 120° to 150°

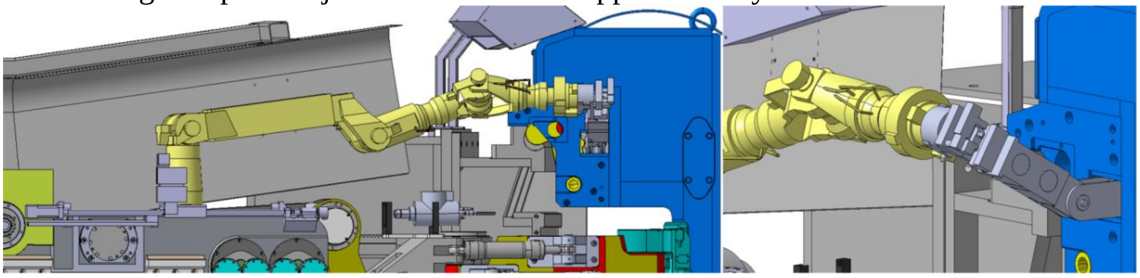


Figure 82: WHMAN unfolding WHJ

- WHMAN joints are continuously adjusted in order to insert WHJ approximately 50 mm into its slot with a linear trajectory.
- This translation aims at increasing the clearance between WHMAN and the right hand side SC.

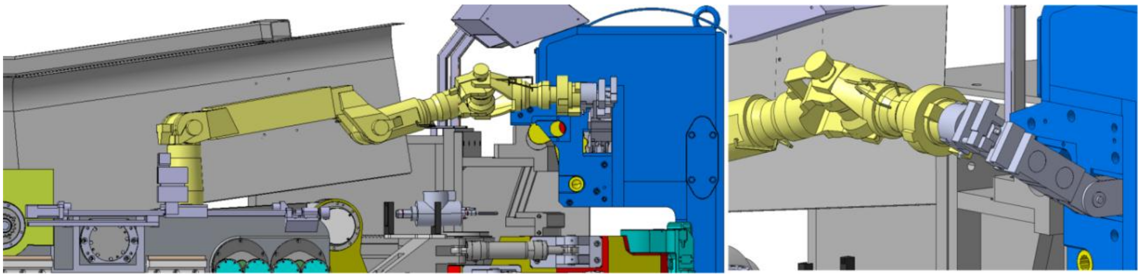


Figure 83: Translation of WHJ

- WHMAN joints are continuously adjusted in order to unfold WHJ with a circular trajectory.
- The passive joint of WHJ turns fully unfolded.

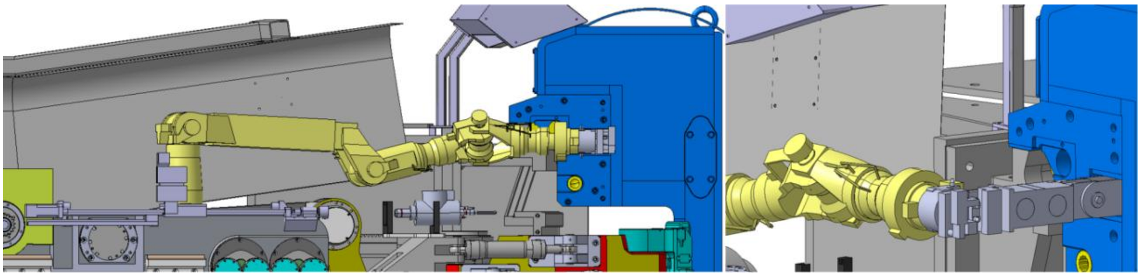


Figure 84: WHJ unfolded

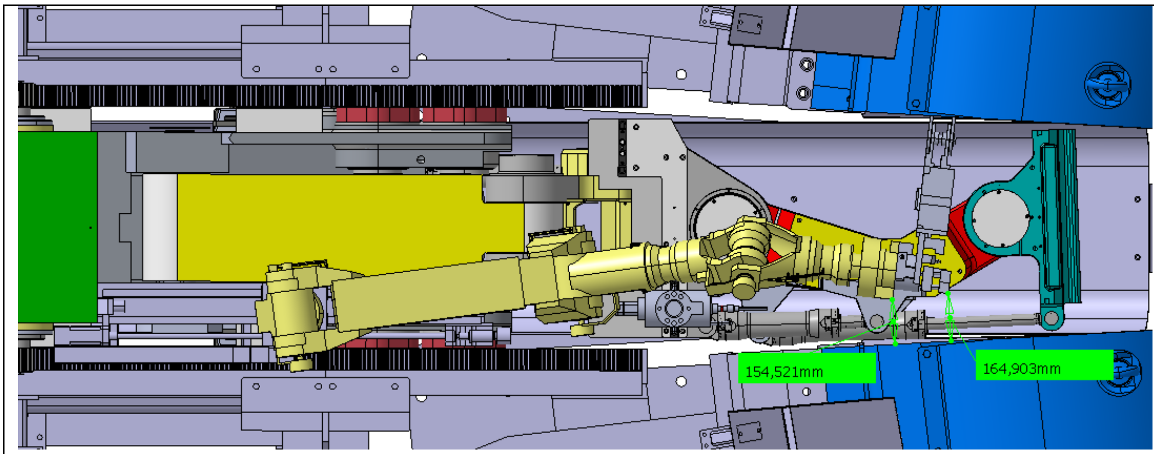


Figure 85: Clearances during the pre-positioning of WHJ

- WHMAN is set in position to align the WHJ stopper with SC CLS side panel (at the same time the pushing parts of WHJ meets the latches).
- WHMAN joints are continuously adjusted in order to insert WHJ with a linear trajectory to its slot.

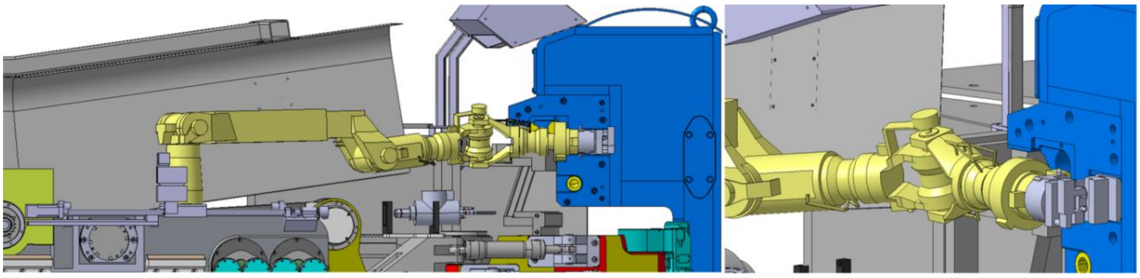


Figure 86: WHJ fully inserted

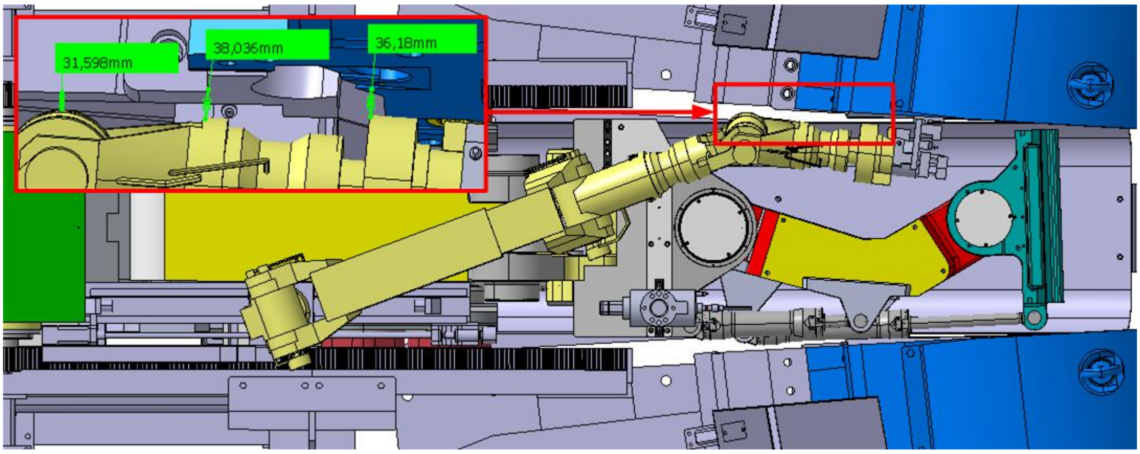


Figure 87: Clearances when WHJ is fully inserted

5.4 Compression process of the Second Cassette

The compression process of the SC is executed by pressurization of the WHJ. The process can be split to few steps. Firstly, WHJ pistons meet the cassette and pushing plates meet latches. Secondly, cassette is sliding towards the inner rail to the position where SC nose matches its vessel counterpart. Lastly, SC is compressed 19 mm to the final position by the WHJ.

- The Pushing plates of WHJ make contact with the latches in order to push and preload the SC. WHJ pistons are pushed outward approximately 5 mm.
- Second Cassette is initially pushed by WHJ. At this new position, the nose of the cassette enters into contact with its Divertor counterpart.

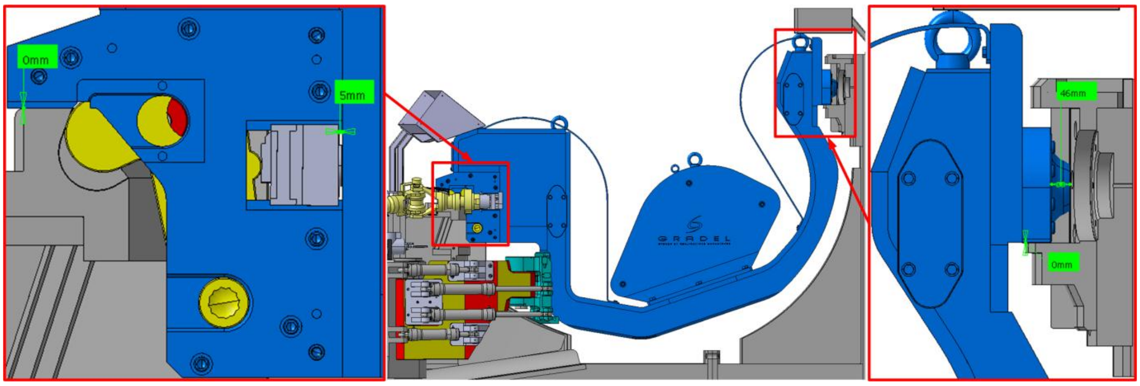


Figure 88: Pushing plates are in contact with latches

- WHJ applies 280 kN to compress the Second Cassette. As a result of a spring-effect, the cassette is compressed 19 mm. WHJ pistons are pushed outward approximately 41 mm.
- WHMAN is moving slightly with WHJ during the compression process.
- WHMAN is detached from WHJ after the compression process and the WHJ will remain pressurized in its slot.

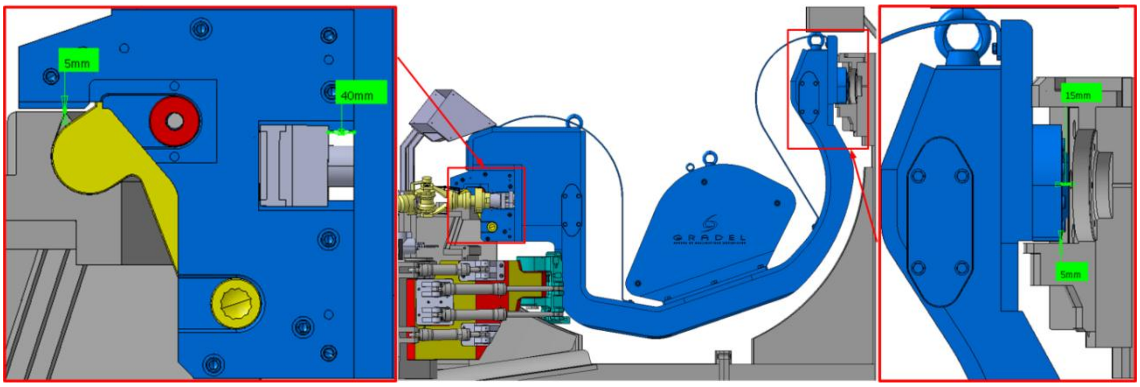


Figure 89: SC final position, after the compression process

6. Locking of the CLS

Cassette latches locking can be split in five different stages:

6.1 Connect WHMAN to the pin tool
6.2 Reach the pin tool to the pin slot
6.3 Insert the pin tool in the pin slot
6.4 Locking the latch of the CLS
6.5 Place the pin tool back on the toolrack

6.1 Connect WHMAN to the pin tool

- WHMAN joints are continuously adjusted in order to insert the wrist into the pin tool with a linear trajectory.

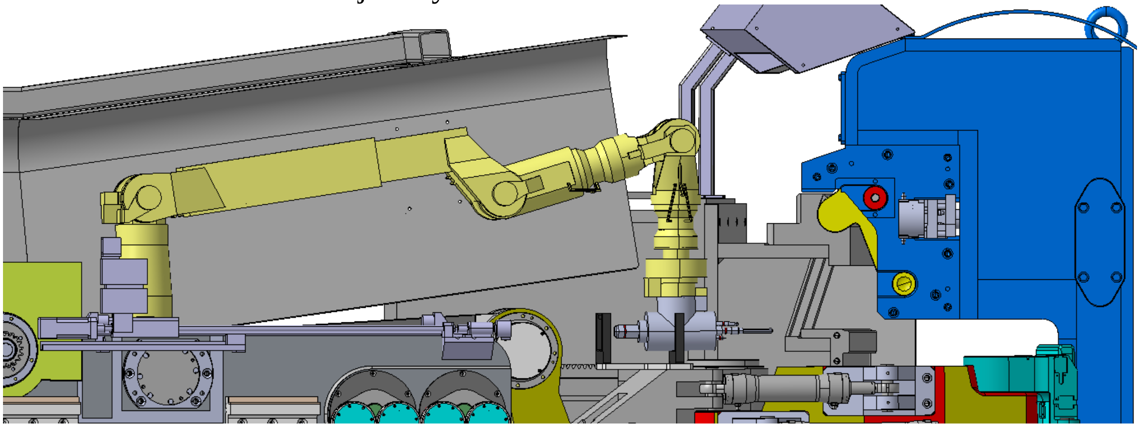


Figure 90: Connecting WHMAN to the pin tool

6.2 Reach the pin tool to the pin slot

- WHMAN joints are continuously adjusted in order to lift the pin tool off from the U-support of toolrack with a linear trajectory.

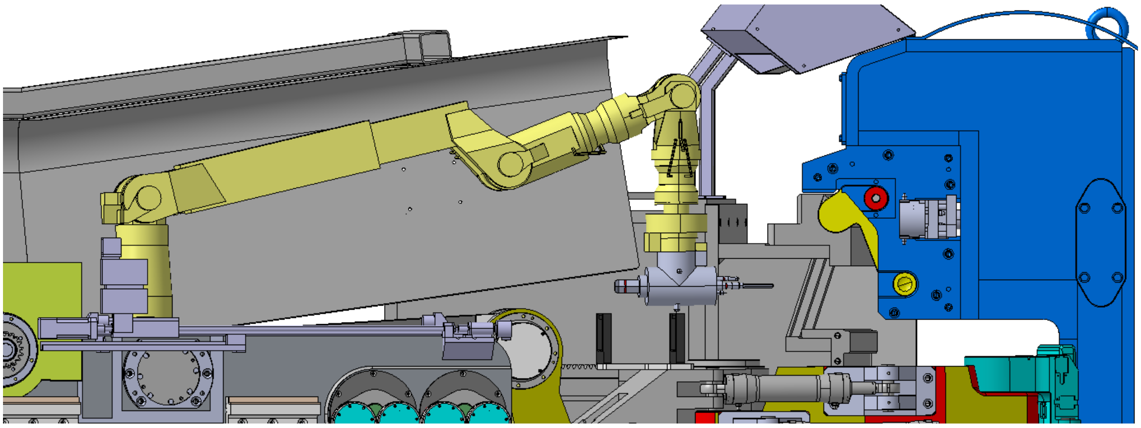


Figure 91: Lifting the pin tool from U-support

- Sliding table moves forward to the working position of the pin tool
- WHMAN joint are continuously adjusted in order to align the pin tool coincident with the pin slot.

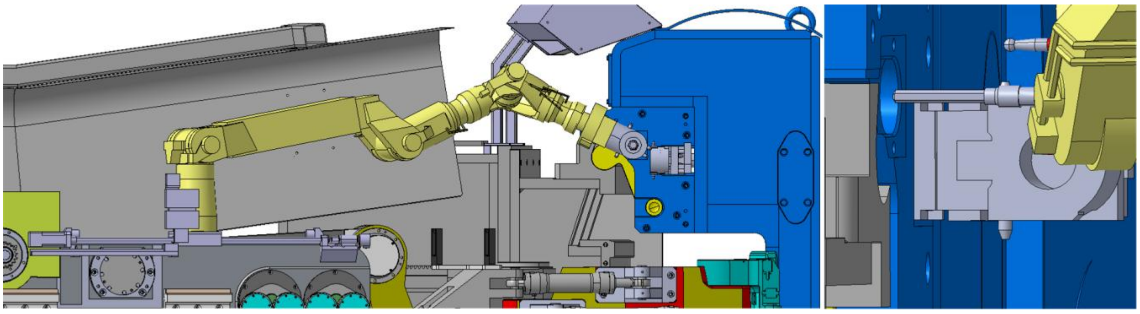


Figure 92: Reach the pin tool to pin slot and illustrated camera view

6.3 Insert the pin tool in the pin slot

- WHMAN joints are continuously adjusted in order to insert the pin tool with a linear trajectory parallel into the locking screw hex socket until the red grooves are disappeared into the cassette side panel (visual verification with camera).

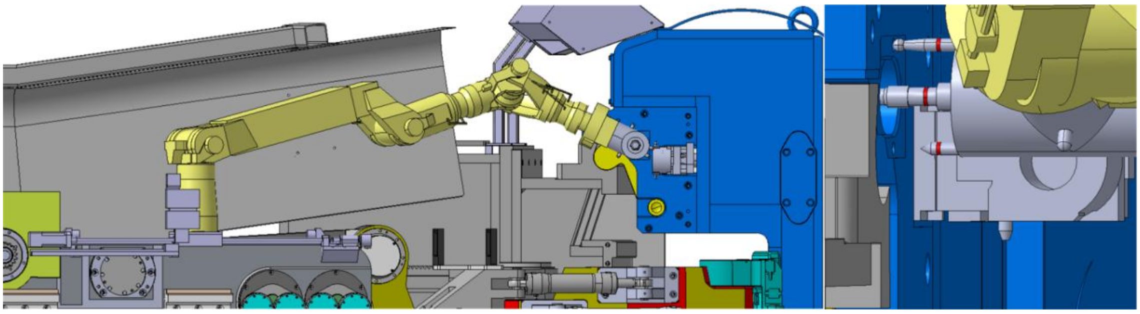


Figure 93: Inserting the pin tool into the pin slot and illustrated camera view

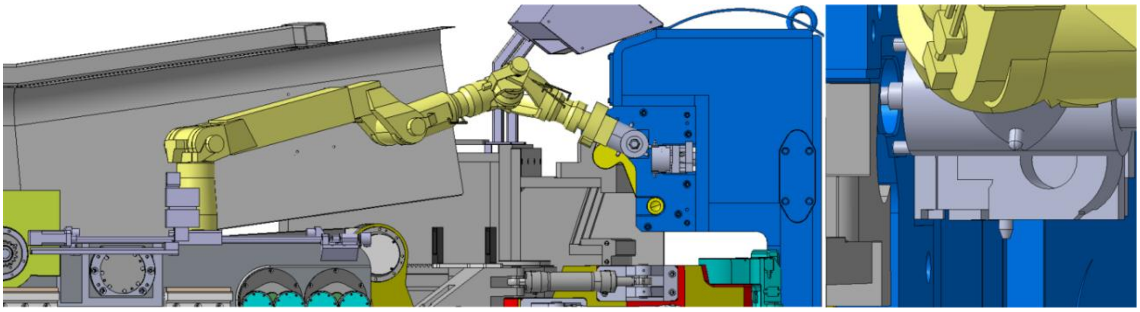


Figure 94: Inserting the pin tool into the pin slot and illustrated camera view

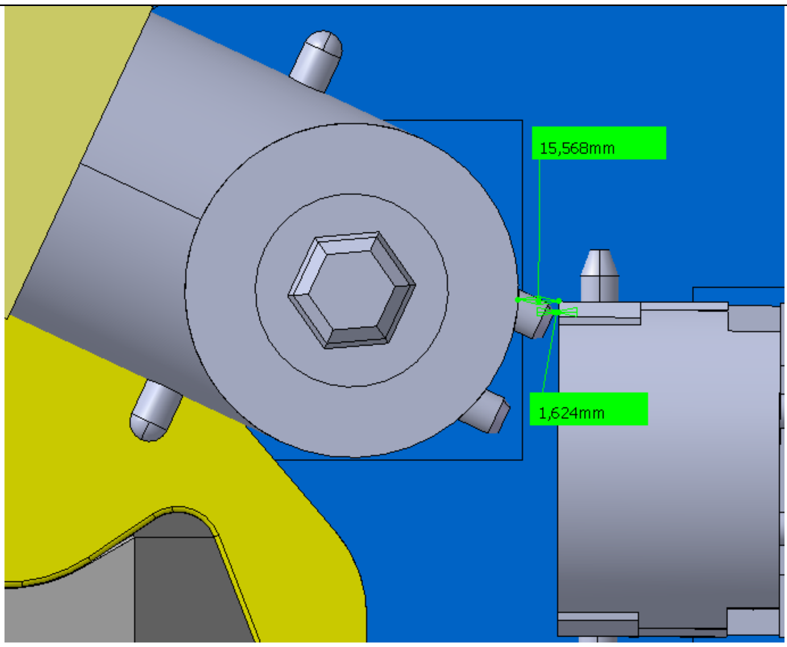


Figure 95: Clearances between the pin tool and WHJ

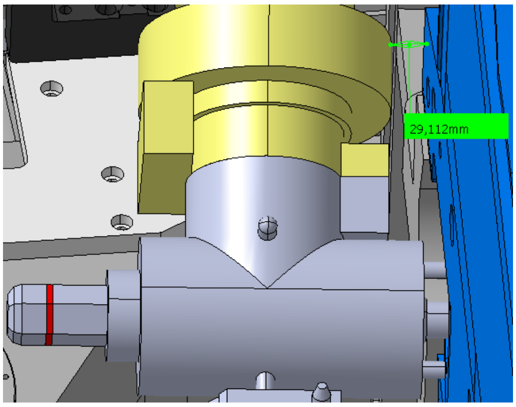


Figure 96: Clearances from WHMAN to SC when the pin tool is fully inserted

6.4 Locking the latch of the CLS

- The electric motor of pin tool rotates the pin mechanism which locks the SC in the DRM. Locking Pins insertion status can be confirmed by using sensors (by revolution of the locking pins). The locking pin moves out 157 mm.

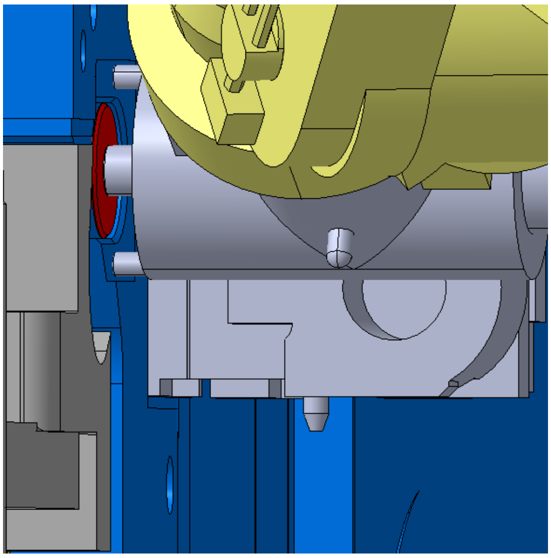


Figure 97: Locking the latch of the SC illustrated from camera view

6.5 Place the pin tool back on the toolrack

- WHMAN joints are continuously adjusted in order to remove the pin tool from the pin tool slot with a linear trajectory.

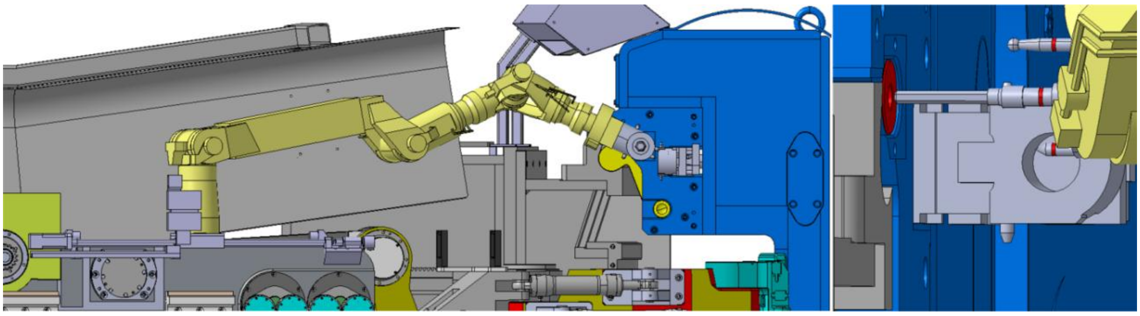


Figure 98: Removing the pin tool from the pin slot and illustrated camera view

- Sliding table moves backward to the home position.
- WHMAN joints are continuously adjusted in order to alignment the pin tool co-incident with the U-support of toolrack.

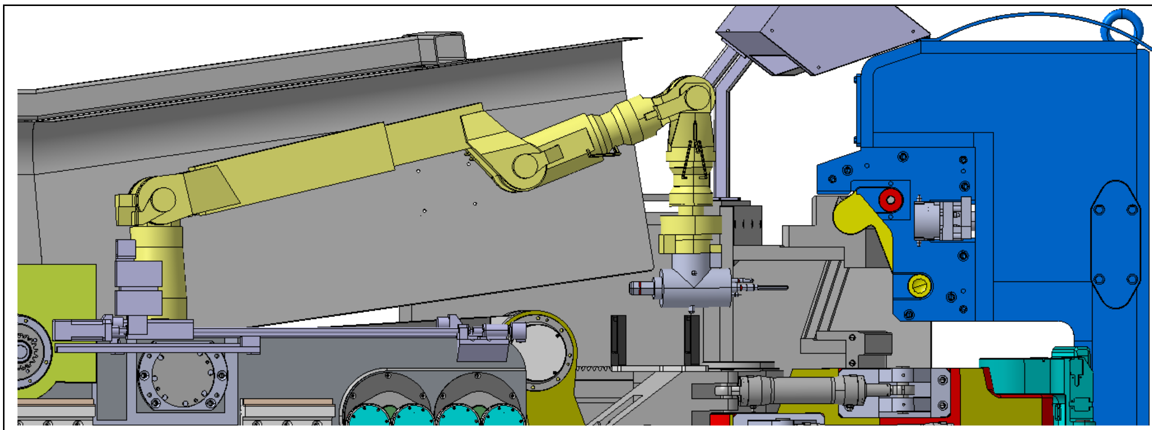


Figure 99: Lowering the pin tool on the U-support

- WHMAN joints are continuously adjusted in order to lower the pin tool back to the U-support of toolrack with a linear trajectory.

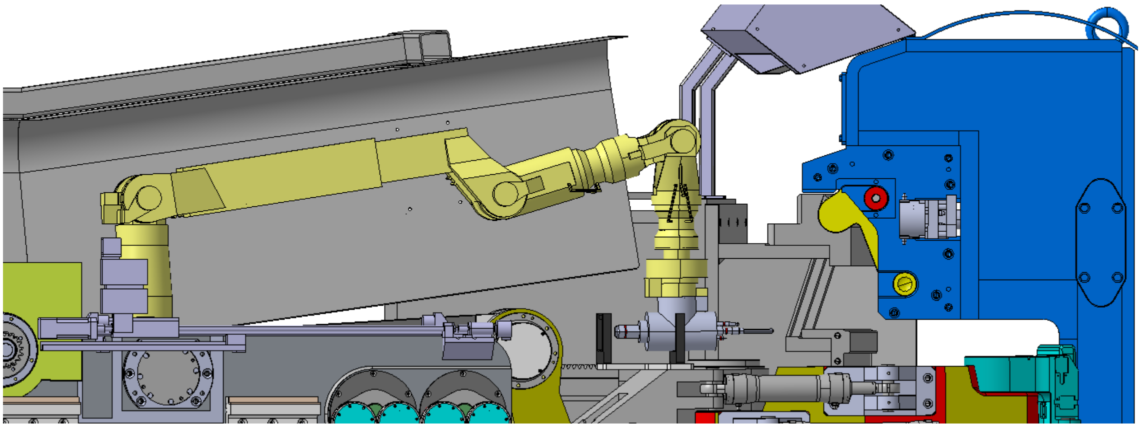


Figure 100: Releasing the pin tool on the toolrack

7. Removal of WHJ

The removal of WHJ can be split in four different stages:

7.1 Connect WHMAN to WHJ
7.2 Depressurization of WHJ
7.3 Fold WHJ
7.4 Place WHJ back on the toolrack

7.1 Connect WHMAN to WHJ

- Sliding table moves forward to the working position of WHJ.
- WHMAN joints are continuously adjusted in order to insert the tool exchanger into the WHJ with a linear trajectory.

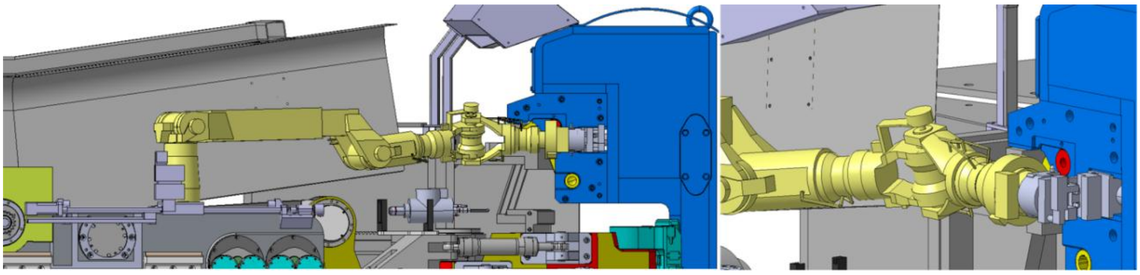


Figure 101: Connecting WHMAN to WHJ

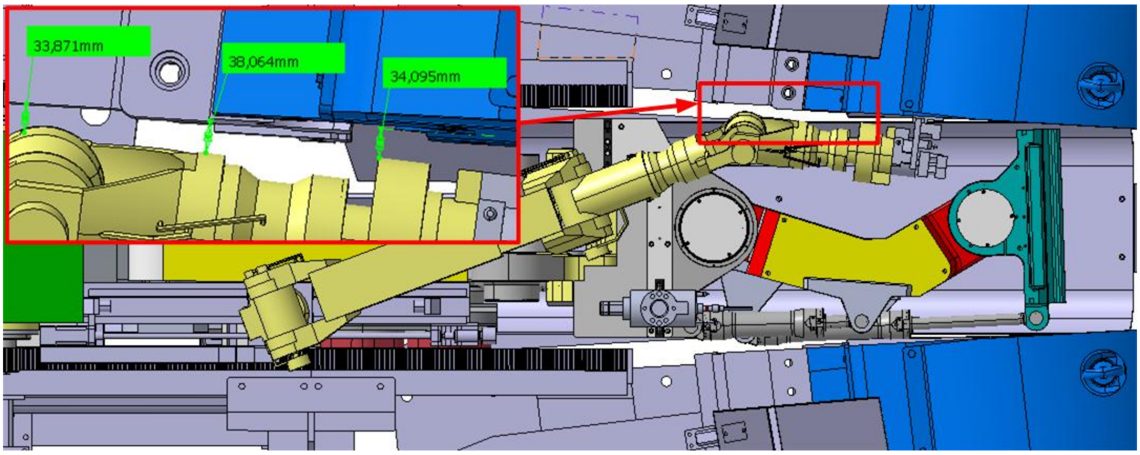


Figure 102: Clearances during connection

7.2 Depressurization of WHJ

- WHJ is depressurized.
- WHJ is set in a position to be removed without collision with the locking system.

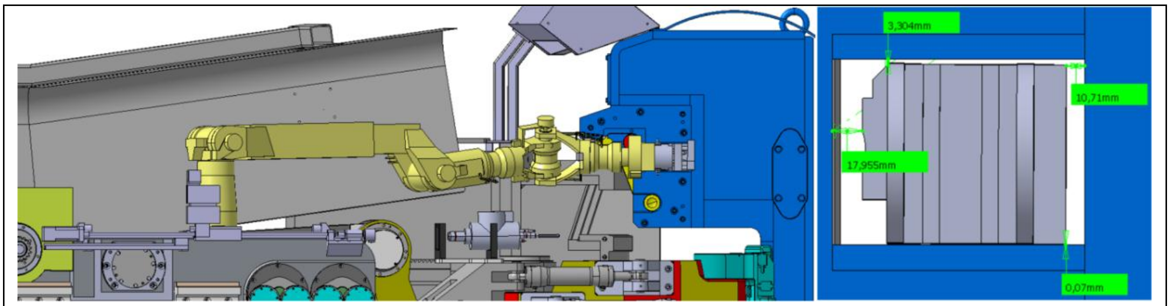


Figure 103: Depressurization of WHJ

7.3 Folding the WHJ

- WHMAN joints are continuously adjusted in order to remove WHJ with a linear trajectory.

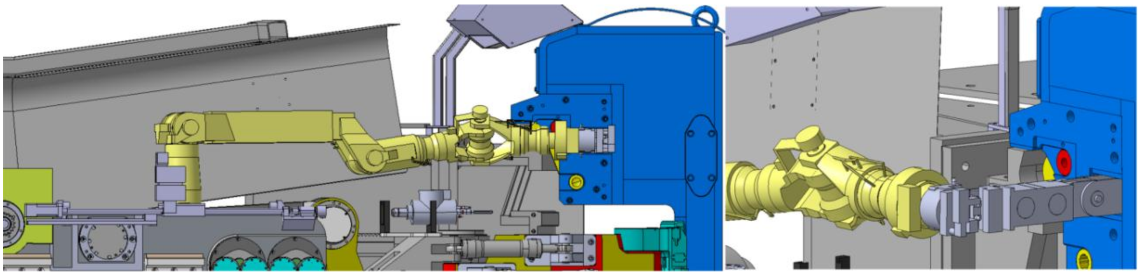


Figure 104: Translation of WHJ

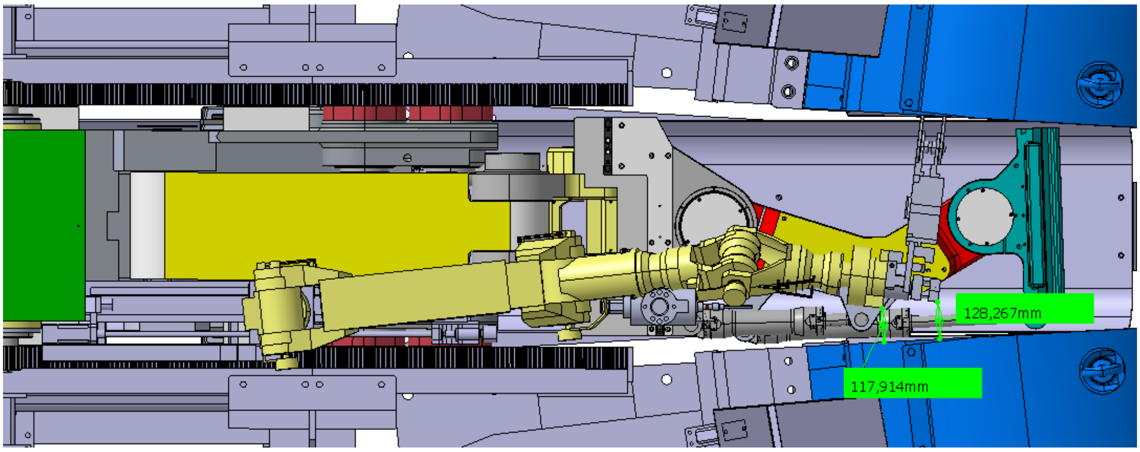


Figure 105: Clearances during folding process

- WHMAN joints are continuously adjusted in order to fold WHJ with a circular trajectory.
- Angle of passive joints of WHJ turns approximately 180° to 150°

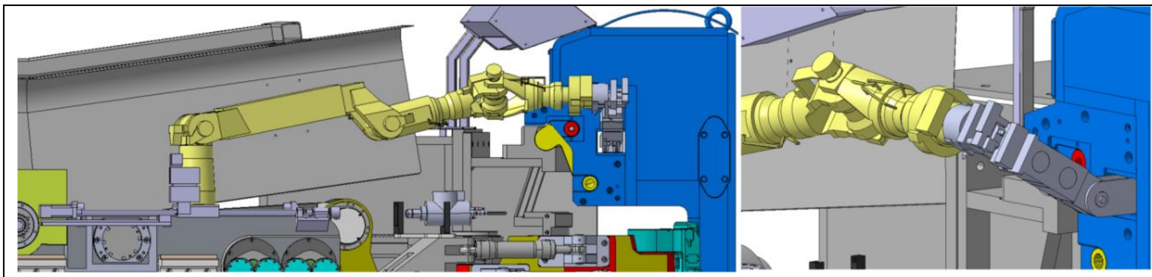


Figure 106: WHMAN folding WHJ

- WHMAN joints are continuously adjusted in order to remove WHJ with a linear trajectory approximately 135 mm.
- This translation aims at increasing the clearance between WHMAN and SC.

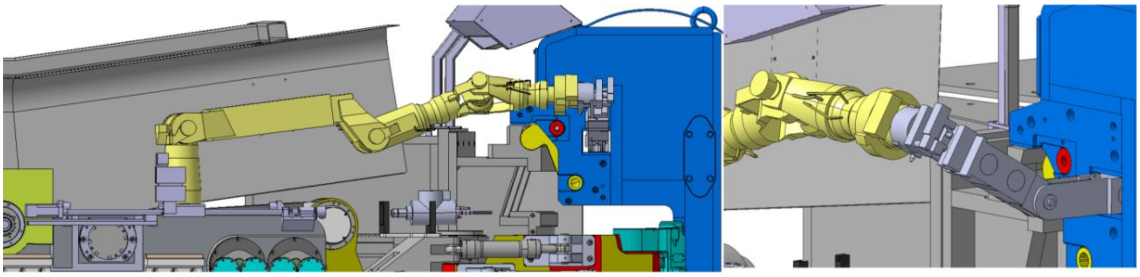


Figure 107: Translation of WHJ

- WHMAN joints are continuously adjusted in order to fold WHJ with a circular trajectory.
- Angle of passive joints of WHJ turns approximately 150° to 120°.

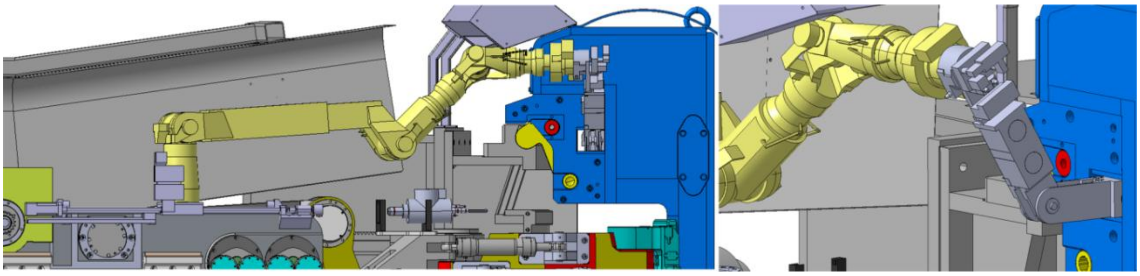


Figure 108: WHMAN folding WHJ

- The posture of WHMAN changes to be able to complete the folding of WHJ.
- The sliding table moves forward.
- WHMAN joints are continuously adjusted in order to keep WHJ at the same position.

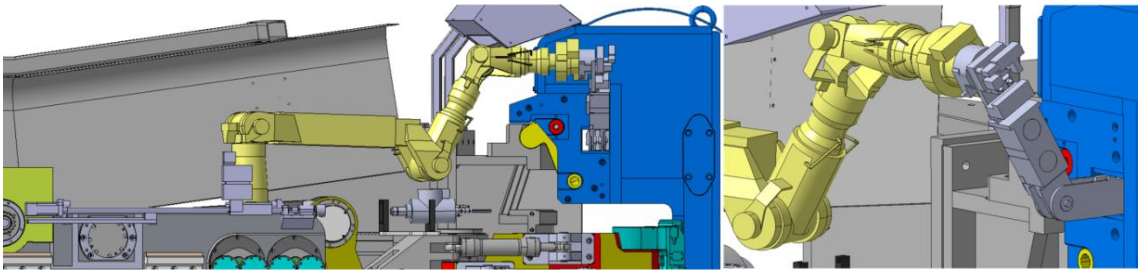


Figure 109: Sliding table moves forward

- WHMAN joints are continuously adjusted in order to fold WHJ with a circular trajectory.
- Angle of passive joints of WHJ turns approximately 120° to 100°.

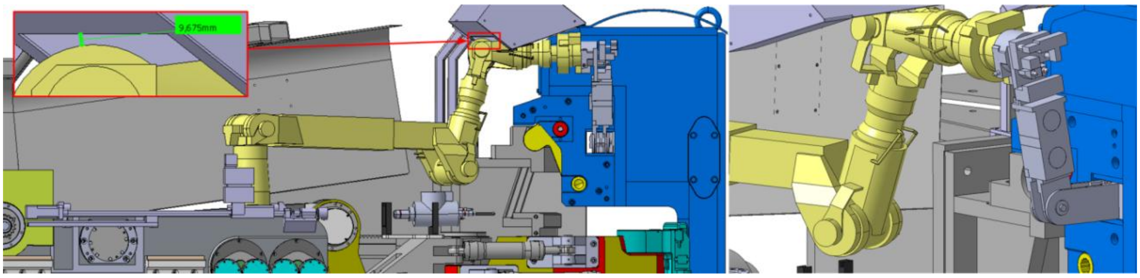


Figure 110: WHMAN folding WHJ

- WHMAN joints are continuously adjusted in order to remove WHJ with a linear trajectory approximately 100 mm.
- This translation aims at increasing the clearance between WHMAN and the upper part of DRM (clearance increases from 9 mm to 10 mm).

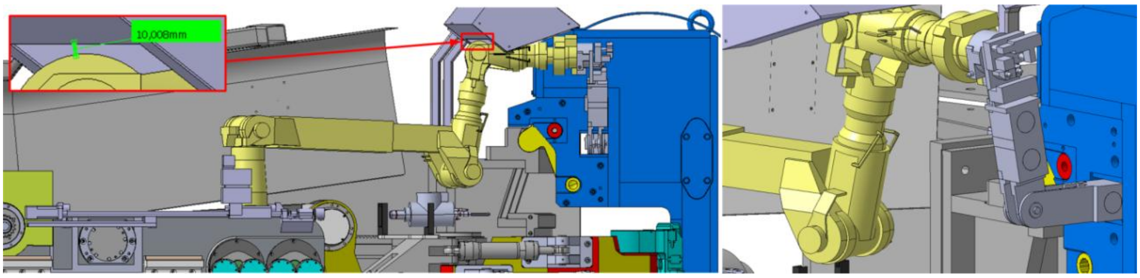


Figure 111: Translation of WHJ

- WHMAN joints are continuously adjusted in order to fold WHJ with a circular trajectory.
- The passive joint of WHJ turns fully folded.
- A clearance of 9 mm appears between WHMAN and the upper part body of the DRM with the current models using the joint limits of WHMAN.

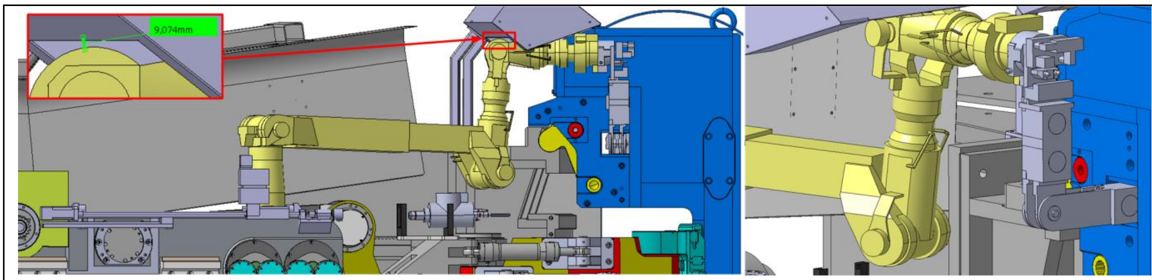


Figure 112: WHJ folded

7.4 Place WHJ back on the toolrack

- WHMAN joints are continuously adjusted in order to remove WHJ with a linear trajectory parallel to the cassette slot´s direction.
- The trajectory of the wrist is linear to avoid collision with the DRM.
- A clearance of 5,7 mm appears between WHMAN and the upper part body of the DRM with the current models using the joint limits of WHMAN.

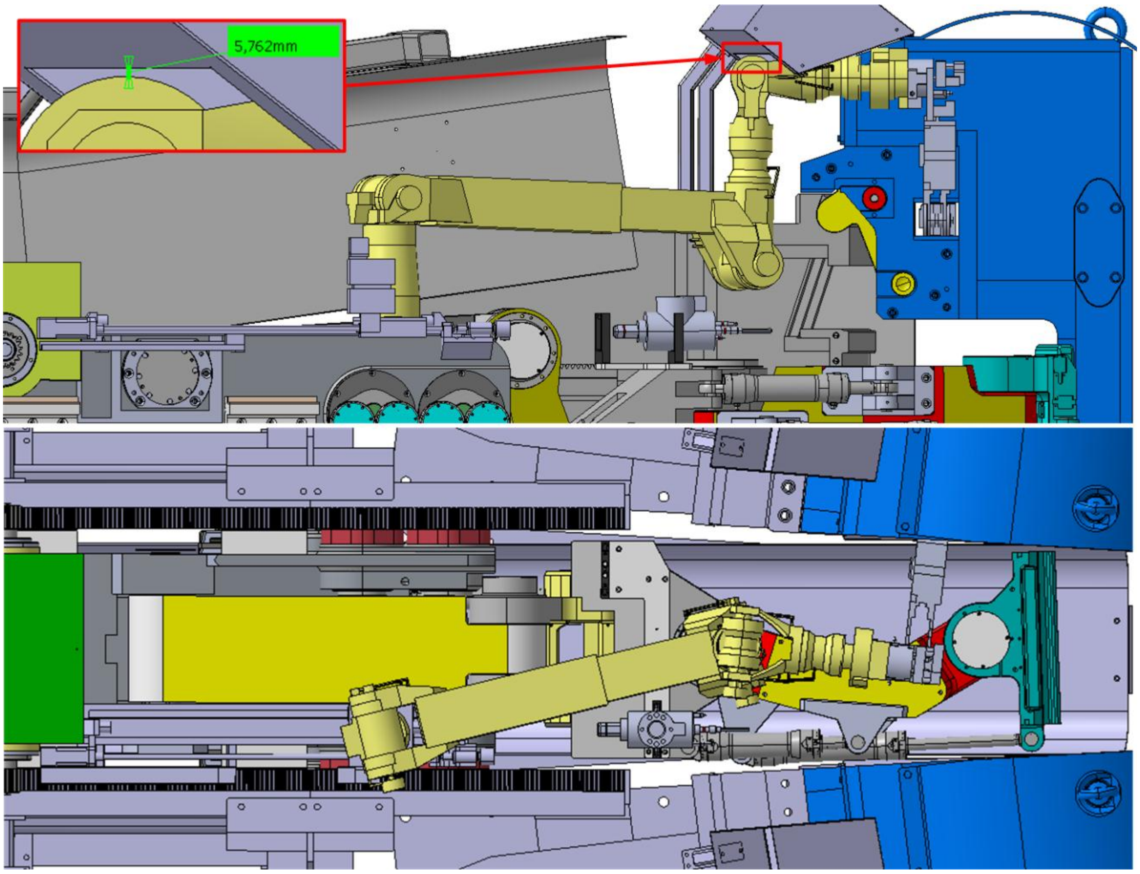


Figure 113: Turning the WHJ back on the toolrack

- WHMAN joints are continuously adjusted in order to turn the WHJ in the DRM back to coincident with the U-support of toolrack.

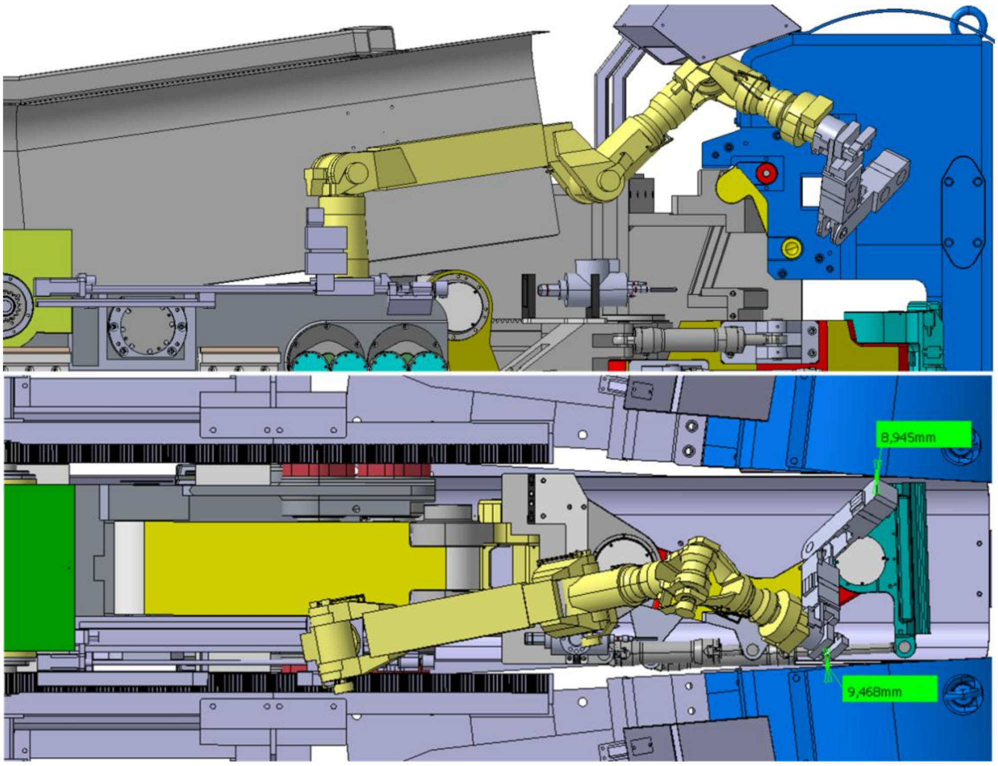


Figure 114: Turning the WHJ back on the toolrack

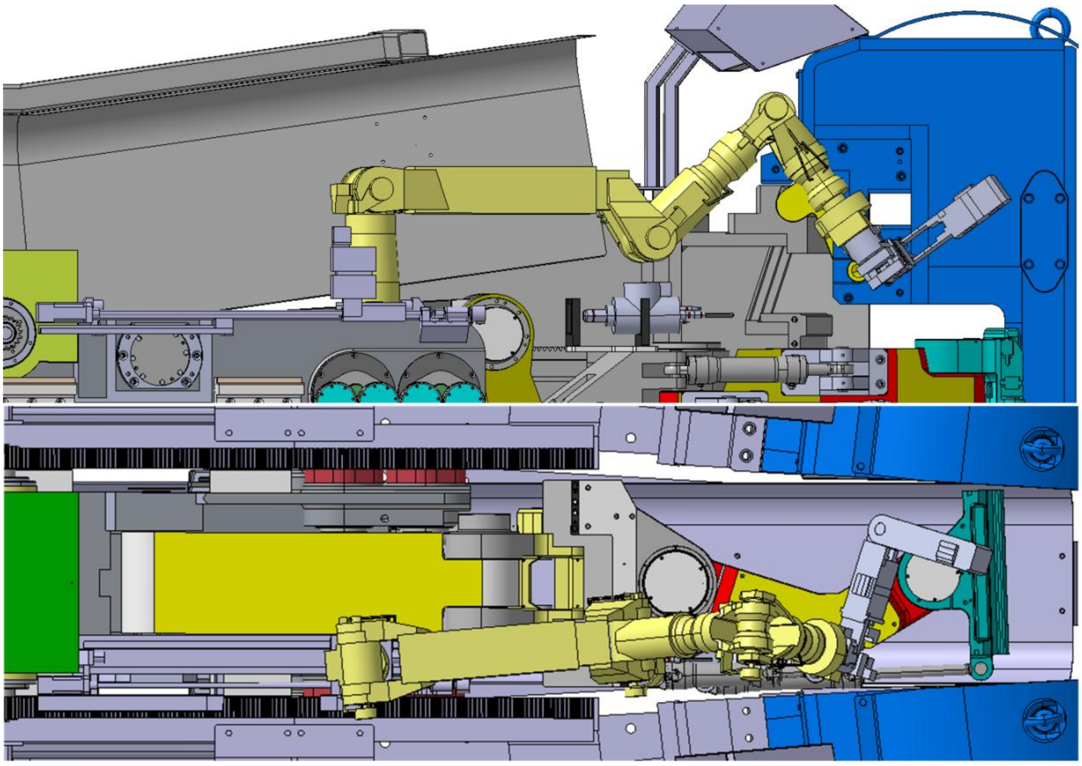


Figure 115: Turning the WHJ back on the toolrack

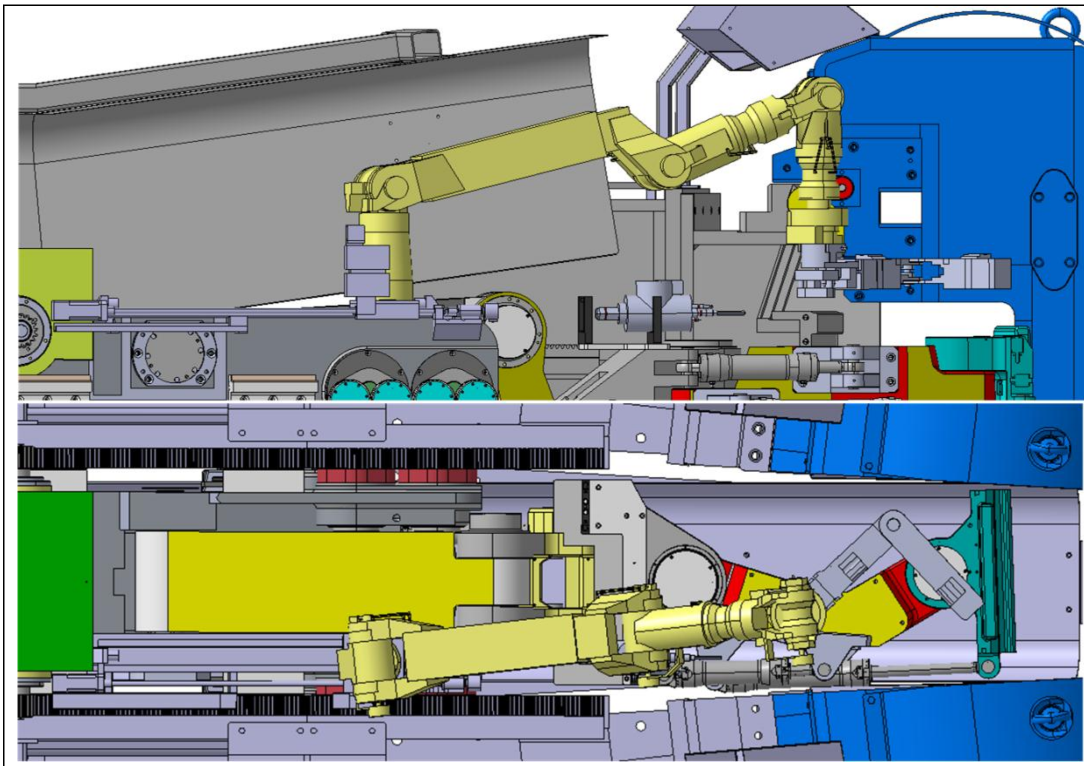


Figure 116: Turning the WHJ back on the toolrack

- Sliding table moves backward to the home position

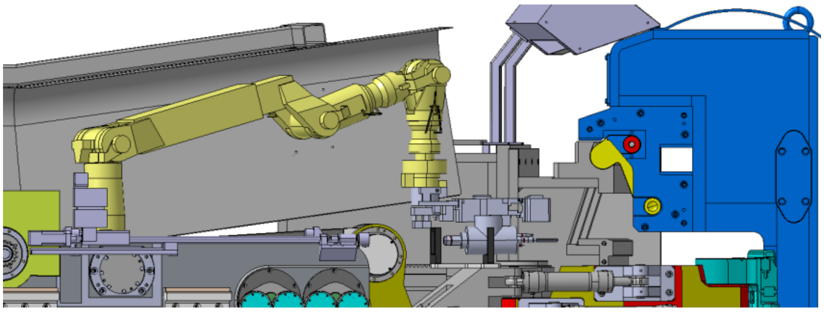


Figure 117: Lowering the WHJ tool on the U-support

- WHMAN joints are continuously adjusted in order to insert the WHJ back to the U-support

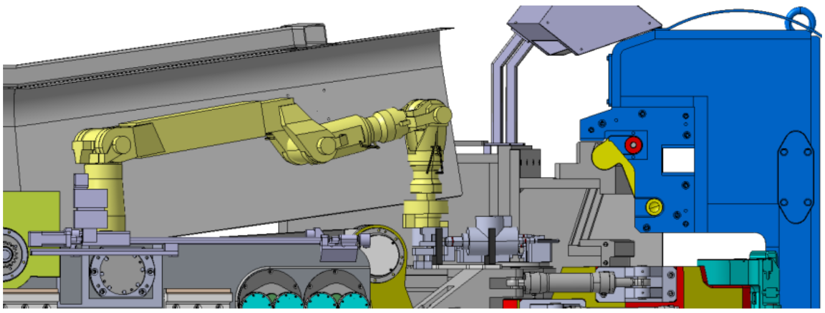


Figure 118: Releasing the WHJ on the toolrack

Validation of the RH Task against the available WHMAN joint positions

In this section, the value of the WHMAN joint positions is tabulated for each of the sequence described in the RH Task definition. Based on the results in table 9, it can be concluded that the RH task is compatible with the range of motions provided by WHMAN.

Table 9: Joint positions of WHMAN and CMM during the RH Task "Locking of the Second Cassette in DRM"

Values of the joints of the CMM	Joint 1 (mm)	Joint 2 (deg)	Joint 3 (deg)	Joint 4 (deg)	Joint 5	Joint 6 (deg)
Position SC released (1)	12026,512	6,386	-1,220	46,929	-53,584	0
Position zero (2 - 6)	11700,000	3,579	1,558	2	0	0

WHMAN Joint Limits:	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6	Joint 7	Sliding Table
Min value	-45	-30	0	-180	-135	-135	-45	0
Max value	225	90	400	90	135	135	225	832
Used values of the joints for the following positions :	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6	Joint 7	Sliding Table
1 - 2	0,00	0,00	310,00	-178,00	0,00	0,00	0	0
3.1	1,50	26,00	250,00	-178,00	0,00	0,00	0	832
3.2.1	13,25	25,25	270,00	-129,00	0,00	-100,00	0	832
3.2.2	13,25	25,25	240,00	-49,00	0,00	-130,00	0	832
3.3.1 - 3.3.2	13,25	15,25	240,00	5,00	0,00	-130,00	0	832
3.3.3 - 3.3.4	5,00	15,75	0,00	-25,24	0,00	9,49	0	832
4.1. – 4.5.2	0,346	83745	192,070	7,931	1,023	-106,364	0,640	0
4.2.1 – 4.5.1	0,220	13,208	214,646	8,548	1,055	-111,446	0,611	0
4.2.2	15,214	9,291	366,818	14,284	-7,563	-91,667	110,395	465
4.3	16,194	9,095	381,791	14,773	-7,929	-92,078	111,245	465
4.4	18,049	8,987	220,040	8,868	-15,222	-72,071	115,070	465
5.1 - 7.4.6	19,996	9,296	52,777	4,403	0,842	-103,077	200,194	0
5.2.1 - 7.4.5	19,906	15,135	78,049	5,091	0,875	-109,604	200,206	0
5.2.2	6,208	14,121	0,00	9,215	1,026	-112,926	143,497	830
5.2.3	4,962	-0,018	0,00	43,382	-11,983	-99,394	106,819	830
5.2.4	10,773	8,202	0,00	34,554	-34,700	-77,478	68,017	830
5.2.5	14,137	-2,193	250,462	88,911	-20,877	-87,131	2,152	830
5.2.6	23,410	-1,970	362,900	89,600	-30,090	-88,020	2,272	830
5.3.1	14,050	-2,037	0,00	64,480	-23,093	-64,338	41,484	830
5.3.2	13,700	0,670	219,000	54,170	-24,370	-57,730	44,610	478
5.3.3	7,853	7,585	0,00	12,414	-36,697	-24,901	95,025	478
5.3.4	9,587	9,840	0,00	6,398	-45,582	-23,147	104,158	478
5.3.5	7,495	-2,771	0,00	16,945	-45,161	-20,261	134,294	478
5.3.6	20,379	1,502	113,937	6,028	-74,815	-28,164	163,954	478
5.4.1	20,114	1,566	107,165	5,855	-74,851	-27,882	164,034	478
5.4.2 – 7.1	20,479	1,731	107,378	5,860	-74,767	-28,276	163,885	478
6.1 - 6.5.3	0,346	8,745	192,070	7,931	1,023	-106,364	180,640	0
6.2.1 - 6.5.2	0,220	13,208	214,646	8,548	1,055	-111,446	180,611	0
6.2.2 - 6.5.1	16,011	10,610	0,00	14,126	-24,909	-54,346	116,083	425
6.3.1	19,959	14,254	27,593	3,694	-31,353	-50,088	124,237	425
6.3.2 - 6.4	21,620	13,808	53,174	4,414	-32,847	-54,159	125,780	425
7.2	19,747	1,493	130,021	6,435	-73,686	-27,669	162,773	478
7.3.1	6,139	-0,736	0,00	11,998	-48,441	-17,302	138,072	478
7.3.2	8,228	11,194	7,422	3,042	-46,544	-20,814	105,574	478
7.3.3	3,501	7,249	0,00	13,621	-26,419	-23,503	85,422	478
7.3.4	9,492	4,001	182,834	39,909	-22,743	-45,758	47,313	478
7.3.5	13,791	-1,594	19,000	63,154	-22,925	-63,770	42,274	832
7.3.6	19,913	-1,565	194,140	75,712	-27,708	-75,497	18,418	832
7.3.7	15,977	-2,053	217,792	81,274	-23,054	-79,904	15,187	832
7.3.8	19,274	-1,992	311,168	86,700	-25,894	-85,000	3,439	832
7.4.1	13,681	-2,090	284,044	90,000	-20,347	-88,300	2,288	832
7.4.2	10,773	8,202	0,00	34,554	-34,700	-77,478	68,017	832
7.4.3	4,962	-0,18	0,00	43,382	-11,983	-99,394	106,819	832
7.4.4	6,208	14,121	0,00	9,215	1,026	-112,926	143,497	832